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Carbon Negative Heat and Power with Biochar Production

An Economic Analysis of a Combined Pyrolysis and CHP plant

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Approved	Examiner	Supervisor
2020-06-09	Niklas Arvidsson	Fabian Levihn
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Abstract

On the fourth of November 2016, The Paris Agreement entered into force, stating that nations worldwide should pursue efforts to limit the global temperature increase to 1,5 °C. Since then, the Intergovernmental Panel on Climate Change has specified that carbon dioxide removal, such as biochar sequestration, is necessary to achieve this goal. Biochar is a solid and porous material, rich in carbon, produced when biomass undergoes a process called pyrolysis and can, if buried in soil, sequester carbon for hundreds or even thousands of years while at the same time acting as a soil amendment. When biomass is pyrolyzed to produce biochar, a pyrolysis gas is also produced, which can be used to generate both heat and electricity. This thesis investigates if constructing and operating a plant, called a combined pyrolysis and CHP plant, which combines biochar production with heat and electricity generation, could be economically feasible and thus be an effective method for carbon dioxide removal.

The findings show that constructing and operating a combined pyrolysis and CHP plant can be economically feasible. However, the economic feasibility is greatly affected by the price of biochar as a soil amendment product. The biochar market is also an undeveloped market, making price estimates of biochar far from accurate. Another factor that could significantly affect the economic feasibility of the plant is the fraction of carbon in biochar, which can be accounted for as sequestered. A higher fraction means that significantly more governmental support can be given to provide financing of the plant as well as potential revenue from carbon credits could increase. The capital cost of constructing the plant is also a factor with high uncertainty, which has a substantial effect on the economic feasibility. From this thesis, it is concluded that more research regarding the biochar market, as well as the capital costs of constructing the plant, is needed. More research could further ascertain whether or not the plant could be economically feasible and thus, an effective method for carbon dioxide removal.

Key-words

Pyrolysis, Combined Heat and Power, CHP, Biochar, Biomass, CDR, Carbon Sequestration

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Sammanfattning

Den fjärde november 2016 trädde Parisavtalet i kraft vilket uppgav att länder över hela världen ska sträva efter att begränsa den globala temperaturökningen till 1,5 grader Celsius. I enlighet med detta mål har FN:s mellanstatliga klimatpanel, IPCC, specificerat att koldioxid-avlägsnande åtgärder, såsom kolinlagring genom produktion av biokol, är nödvändigt. Biokol är ett fast och poröst material, rikt på kol, som produceras när biomassa genomgår en process som kallas pyrolys. Om biokol blandas ner i jord kan det binda kol i hundratals eller tusentals år samtidigt som det fungerar som jordförbättrare. När biomassa pyrolyseras produceras också en pyrolysgas som kan användas för att generera värme och elektricitet. Det här examensarbetet undersöker om det kan vara ekonomiskt genomförbart att bygga och driva en anläggning, benämnd en kombinerad pyrolys- och kraftvärmeanläggning, som kombinerar biokolsproduktion med värme- och elproduktion för att avlägsna koldioxid från atmosfären.

Resultaten från arbetet visar att det kan vara ekonomiskt genomförbart att bygga och driva en kombinerad pyrolys- och kraftvärmeanläggning. Den ekonomiska genomförbarheten påverkas dock i hög grad av priset på biokol som jordförbättringsprodukt. Marknaden för biokol är dessutom outvecklad vilket gör att priset för biokol osäkert. En annan faktor som i hög grad skulle kunna påverka den ekonomiska genomförbarheten för anläggningen är andelen kol i biokol som kan anses vara lagrad. En högre andel innebär att betydligt mer statligt stöd kan ges för att finansiera anläggningen samt att potentiella intäkter från kolkrediter kan öka. Kapitalkostnaderna för att bygga anläggningen är också en faktor med hög osäkerhet som har stor effekt på den ekonomiska genomförbarheten. Från detta examensarbete dras slutsatsen att mer forskning kring biokolsmarknaden samt kring kapitalkostnaderna för att bygga anläggningen behövs. Detta behövs för att ytterligare fastställa den ekonomiska genomförbarheten hos en sådan anläggning för att avlägsna koldioxid från atmosfären.

Nyckelord

Pyrolys, Kraftvärmeverk, KVV, Biokol, Biomassa, Kolinlagring, Negativa utsläpp

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List of Abbreviations

BQM	Biochar Quality Mandate
CapEx	Capital Expenditures
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
DH	District Heating
EBC	European Biochar Certificate
EUR	Euro
FCI	Fixed Capital Investment
grot	Branches and treetops ("Grenar och trädtoppar" in Swedish)
IBI-BS	International Biochar Initiative Biochar Standards
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISBL	Inside Battery Limits
kW	Kilowatt
kW_e	Kilowatt Electrical
MC	Moisture Content
MLP	Multi Level Perspective
MW	Megawatt
MW_e	Megawatt Electrical
NPV	Net Present Value
O&M	Operating & Maintenance
odt	Oven Dry Tonne
OpEx	Operational Expenditures
OSBL	Outside Battery Limits
RHF	Rotary Hearth Furnace
R&D	Research and Development
SEK	Swedish Krona
Tonne	Metric tonne (1000 kg)
USD	United States Dollar
WACC	Weighted Average Cost of Capital

Currency conversion factors

The Swedish Krona (SEK) have been used as the primary currency in this thesis. To more easily compare monetary values in different currencies, other currencies have been converted to SEK using the currency conversion factors below (Sveriges Riksbank, n.d.). If a monetary value of another currency has been converted to SEK, it is indexed with the symbols shown in parentheses below.

1 EUR (€) = 10,6 SEK
1 USD ($) = 9,5 SEK

Foreword

First and foremost, we would like to thank our supervisor at AFRY, Max Larsson, for your support of this work. It has been inspiring to work on this project with you and your enthusiasm for this project has been very valuable to us. We would also like to direct a special thanks to Carl-Johan Hjerpe at AFRY for providing us with and going through all the technical aspects of the model of a combined pyrolysis and CHP plant. Furthermore, we would like to thank our supervisor at KTH, Fabian Levihn, for your advice throughout the project as well as all opponents at KTH for your feedback on our work. Lastly, we would like to thank the people at Division Energy, Heat & Power at AFRY for welcoming us and creating a great environment for us to write our thesis in.

William Bydén & David Fridlund
Stockholm, 9th June 2020

1 Introduction

Global climate change is perhaps the greatest challenge faced by humans in the 21st century. There is a consensus among researchers that global climate change and an increased average global temperature is a result of anthropogenic greenhouse gas emissions, and amongst them, carbon dioxide emissions (IPCC, 2014). As a response to this, The Paris Agreement was established to "strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" (UNFCCC, 2020).

To limit the global temperature increase to 1,5 °C, it is most likely that Carbon Dioxide Removal (CDR) is needed. In a special report on the impacts of global warming of 1,5 °C, IPCC (2018) states that "All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal" (p.17). CDR is necessary because some economic sectors, such as the transportation sector, are too difficult to decarbonize completely within the time-period available (Tisserant and Cherubini, 2019). In the pathways leading to a limit of global warming of 1,5 °C, several methods for CDR are applied and presented by IPCC (2018). These include Afforestation and Reforestation, Bioenergy Carbon Capture and Storage (BECCS), Enhanced Weathering, Direct Air Carbon Capture and Storage and Soil Carbon Sequestration & Biochar. Of the five CDR methods above, Soil Carbon Sequestration & Biochar is deemed the most feasible method from an economic perspective (IPCC, 2018).

Biochar is a solid and porous material, rich in carbon (Brassard et al., 2016), and has been reported to effectively store carbon between hundreds to thousands of years while at the same time acting as a soil improvement substance (Qambrani et al., 2017). Biochar is produced when organic material, such as biomass, is heated to temperatures typically between 350-700 °C in the absence of oxygen, a process called pyrolysis (Brassard et al., 2016). When biomass is pyrolyzed to produce biochar, a pyrolysis gas is also produced, and 35 to 60% of the energy content in the biomass is eventually contained in the pyrolysis gas (EBC, 2012). This gas can be used as a combustible to generate heat and electricity (Garcia-Perez et al., 2010; Gustafsson, 2013; Vamvuka, 2011) and to sustain the pyrolysis process (Crombie and Mašek, 2014; EBC, 2012).

A reason why biochar is economically advantageous compared to other CDR methods is that the production of biochar results in two commercially viable products, namely biochar as soil amendment and pyrolysis gas as bioenergy (Tisserant and Cherubini, 2019). Biochar as a soil amendment product can increase soil quality (Domingues et al., 2017) and, therefore, has agronomic value. Pyrolysis gas as bioenergy can be used for combined heat and power (CHP) production and, therefore, has economic value in energy markets. Constructing a plant, hereinafter referred to as a combined pyrolysis and CHP plant, where a pyrolysis process is utilised to, on one hand, produce biochar for carbon sequestration and soil amendment purposes and, on the other hand, produce pyrolysis gas for CHP generation could, therefore, be an economically feasible method for CDR and thus help mitigate global climate change.

In line with the Paris agreement, the Government of Sweden decided in 2018 that a special investigation with the task of proposing a strategy for how Sweden should reach negative greenhouse gas emissions after 2045 was needed (Karlsson, 2020). In January 2020, this investigation was completed and handed over to the Swedish government (Karlsson, 2020). The investigation, authored by Daoson et al. (2020), concluded that biochar could significantly contribute to negative emissions in Sweden before the middle of this century. Additionally, it was determined that, through the production of biochar, the need for biofuel for district heating in Sweden could decrease as heat can be produced from pyrolysis gas instead (Daoson et al., 2020). Furthermore, it was concluded that governmental economic support to biochar production plants, which is given through a fund called Klimatklivet, should continue to be given to promote the technological development of biochar as a method for CDR. The investigation by Daoson et al. (2020) indicates that constructing a combined pyrolysis and CHP plant in Sweden should be further studied as a method for CDR in Sweden.

1.1 Problem statement

If a combined pyrolysis and CHP plant is to be an effective method for CDR, it must be feasible to construct and operate the plant. The economic feasibility of the plant is thus imperative to evaluate. Yet, no studies regarding the economic feasibility of a combined pyrolysis and CHP plant for CDR purposes that consider governmental support from Klimatklivet could be found. This implies that there is a gap in literature which this thesis aims to address.

For a combined pyrolysis and CHP plant to be economically feasible, an investment in the plant must be attractive to investors. The pyrolysis technology is, however, “in the stage of early development, and therefore the ‘true’ costs of producing biochar and associated by-products may not be known at present” (Lehmann and Joseph, 2015, p.814). It is also uncertain what the monetary benefits from biochar are since the biochar market is far from established (Dickinson et al., 2015). Therefore, the costs and benefits of constructing and operating a combined pyrolysis and CHP plant must be estimated in an adequate way. Additionally, financial conditions, such as discount rate and debt-equity financing ratio, as well as cash flows of an investment in the plant, must be taken into account before the economic feasibility of the plant is determined.

Furthermore, sociotechnical factors, such as infrastructural lock-ins and sunk costs, which are prevalent in current energy systems (Geels, 2010), also play a part in determining the feasibility of developing a combined pyrolysis and CHP plant for CDR purposes. Rip and Kemp (1998) point out that understanding the dynamics of technical change is “vital if deliberate technological change is to be part of the solution to climate change problems" (p.328) and that, regarding the development of new technologies, "The many risks and uncertainties make cost–benefit calculation difficult and sometimes completely irrelevant" (p.347). The dynamics of technological change in the CHP sector, specifically in relation to a combined pyrolysis and CHP plant, must therefore also be evaluated to determine the feasibility of developing a combined pyrolysis and CHP plant and its effectiveness as a method for CDR.

1.2 Purpose

The purpose of this thesis is to give a detailed overview of the feasibility of a combined pyrolysis and CHP plant in Sweden for CDR purposes. The main focus is on the economic feasibility of the plant. Costs and benefits of constructing and operating the plant as well as financial conditions and cash flow of an investment in the plant are evaluated to see how they affect the economic feasibility of the plant and the attractiveness of an investment in the plant. Furthermore, the dynamics of technological change in the CHP sector are evaluated to better understand how sociotechnical factors affect the development of a combined pyrolysis and CHP plant. The findings from this thesis could justify or facilitate investigations of future investments of this kind and thus increase the knowledge of the effectiveness of a combined pyrolysis and CHP plant as a method for CDR.

1.3 Research questions

The Main Research Question (MRQ) of this thesis is formulated as:

MRQ: *What are the main parameters influencing the economic feasibility of building and operating a combined pyrolysis and CHP plant?*

To answer the main research question, it will be necessary to answer the following two Sub-Research Questions (SRQs):

SRQ1: *What are the costs of building and operating a combined pyrolysis and CHP plant?*

SRQ2: *What are the potential economic benefits from a combined pyrolysis and CHP plant?*

Additionally, to better understand how the dynamics of technological change in the CHP sector affect the feasibility of developing a combined pyrolysis and CHP plant, the following SRQ was formulated:

SRQ3: *What are the main characteristics of technological change in the CHP sector and how do they affect the development of a combined pyrolysis and CHP plant?*

1.4 Thesis sponsor

This thesis has been conducted in collaboration with the consultant company AFRY (former ÅF Pöyry). AFRY has created a technical model of a combined pyrolysis and CHP plant with calculations of mass and energy balances of the processes in the plant, which the economic analysis in this thesis is based on. The model, with corresponding calculations of mass and energy balances, is partially confidential and is, therefore, not be presented in full in this thesis. However, as the focus of this thesis is on the economic feasibility of the plant, it is not necessary to review all aspects of the model in depth. Instead, the parts of the model which are necessary to evaluate the economic feasibility of the plant are presented in this thesis.

1.5 Delimitations

The context of this thesis is Swedish and aspects such as costs, prices, regulations, and policies are therefore evaluated from a Swedish perspective. Furthermore, as literature regarding plants that combine a pyrolysis process with CHP generation is scarce, especially literature with an economic focus, there is no single acknowledged way of comparing and evaluating investments in such combined plants. In this thesis, it is therefore assumed that an investment in the plant would be compared to an investment in a CHP plant of similar capacity in terms of electrical power and heat output. Lastly, as the economic analysis of a combined pyrolysis and CHP plant is based on the model provided by AFRY, other technical configurations of combined pyrolysis and CHP plants have not been considered in this thesis.

2 Background

In this chapter, the model of a combined pyrolysis and CHP plant is presented and pertinent literature regarding the plant and plant economics are reviewed to provide a solid foundation for evaluating the economic feasibility of the plant. A theoretical framework for analysing the dynamics of technological change in the CHP sector is also presented.

2.1 Model overview of a combined pyrolysis and CHP plant

The model of a combined pyrolysis and CHP plant developed by AFRY can be said to consist of two parts; a pyrolysis part and a CHP part. The major processes in the pyrolysis part are mechanical dewatering of biomass, drying of biomass, pyrolysis of biomass, cooling of biochar, and partial combustion of pyrolysis gas to sustain the pyrolysis process. The major processes in the CHP part are full combustion of pyrolysis gas, steam generation, steam turbine electricity generation, and condensing of steam for district heating. A general system diagram with the major processes and flows in the plant is shown in Figure 1.

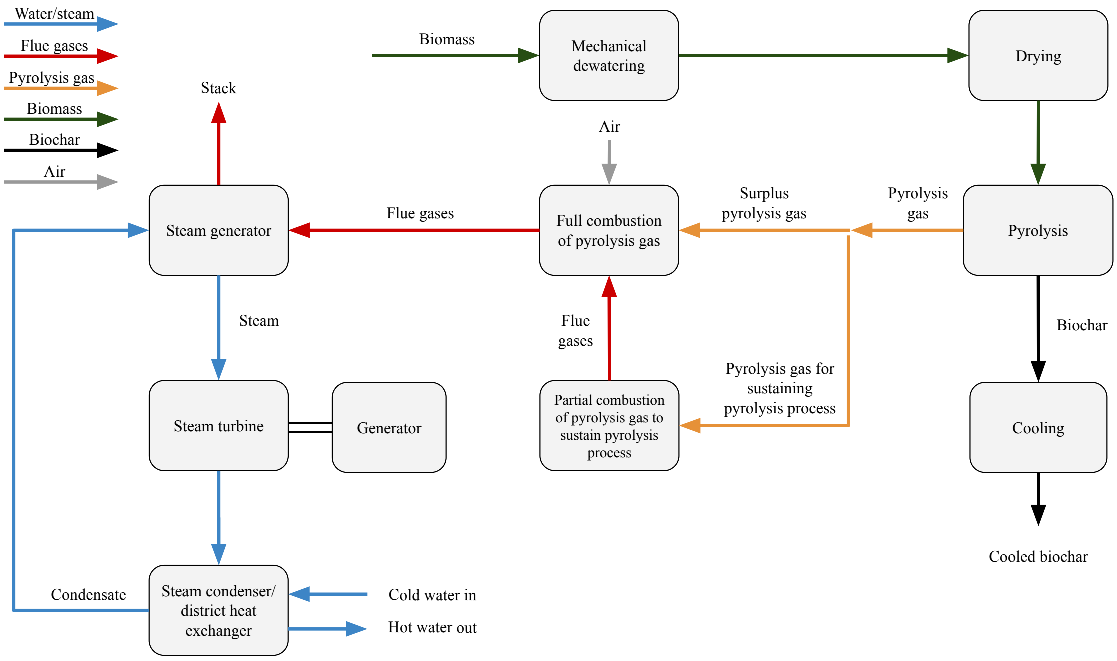

Figure 1. General system diagram showing the main processes and flows in the combined pyrolysis and CHP plant.

As shown in Figure 1, biomass is first mechanically dewatered and dried before it is pyrolyzed in a furnace. The biochar resulting from the pyrolysis process is cooled for easier handling. A part of the pyrolysis gas is combusted in the furnace to sustain the pyrolysis process, while the surplus pyrolysis gas is fully combusted in an afterburner. The hot flue gas resulting from the combustion of pyrolysis gas is then utilised to generate steam, which, in turn, is used to generate electricity and heat in a district heating system. An illustration of the plant is shown in Figure 2, and a more detailed illustration of the steam generation, steam turbine electricity generation, and condensing of steam is shown in Figure 3. In chapter 2.2, the mechanical dewatering and drying of biomass are explained in further detail. In chapter 2.3, the pyrolysis process and corresponding furnace used for pyrolysis are reviewed, and, in chapter 2.4, the CHP production in the plant is explained.

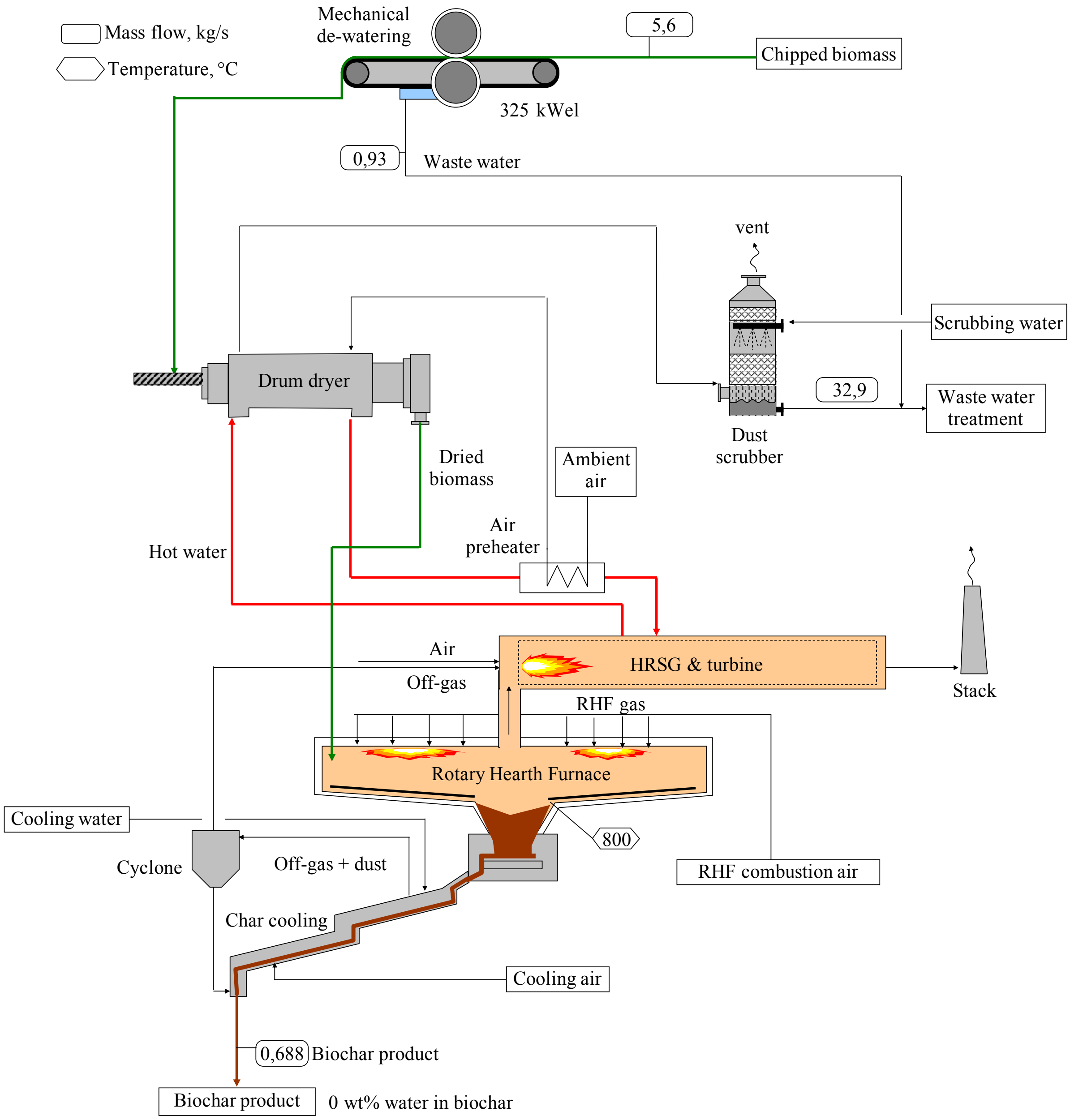

Figure 2. Illustration of the combined pyrolysis and CHP plant.

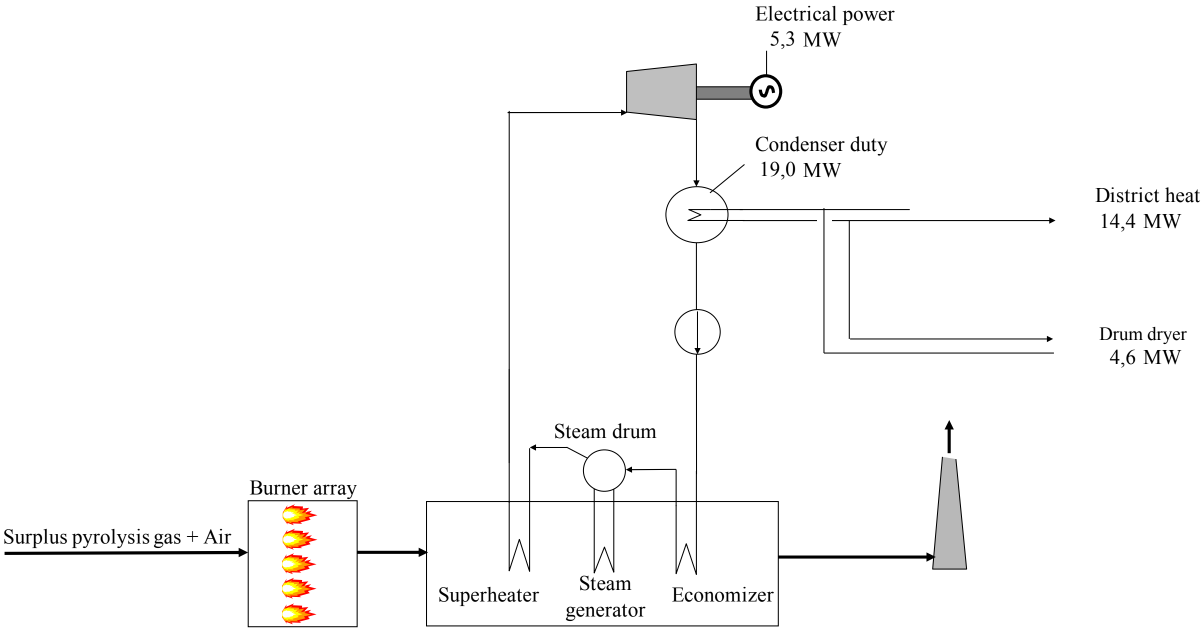

Figure 3. Illustration of the steam generation, steam turbine electricity generation and condensing of steam in the combined pyrolysis and CHP plant.

2.2 Biomass

Biomass is the raw material used in the plant for producing biochar and generating electricity and heat. Biomass can be defined as "matter originating from living plants, including tree stems, branches, leaves as well as residues from agricultural harvesting and processing of seeds or fruits" (Pang, 2016, p.243). Biomass contains carbon but can, in contrast to fossil fuels, be considered a renewable energy source as the burning of biomass does not cause a net addition to carbon dioxide levels in the atmosphere (Basu, 2013). In a well-managed forest system, it is even possible to increase both the biomass harvest and carbon storage simultaneously (IRENA, 2019). Börjesson (2016) writes that the biomass-economy is expected to grow and that Sweden, due to its great forest resources, has the potential to increase the amount of energy and products deriving from biomass. There is especially a great potential of better utilising residues from forest felling and thinning, such as branches and treetops (also known as grot), which is otherwise left for degradation (IRENA, 2019; Svebio, 2019). According to IRENA (2019), the annual amount of grot utilised in Sweden has the potential to increase from 10 TWh to 33 TWh while still being sustainable.

The biomass used as input to the plant is grot. The grot is comparable to the Swedish grot studied by Strömberg and Herstad Svärd (2012), as shown in Table 1. The only difference in the grot composition used in the model compared to the Swedish grot studied by Strömberg and Herstad Svärd (2012) is that the grot in the model has a moisture content (MC) of 50%, instead of 47,9%. A prerequisite for the processes in the plant is that the grot is chipped before entering the plant. The biomass input to the plant is 20 tonne wet biomass (i.e. biomass with an MC of 50%) per hour, and the annual operating time of the plant is 8000 hours.

Table 1. Analysis of Swedish grot (Strömberg and Herstad Svärd, 2012).

Density (kg/m^3)	
Bulk density	200-350

Fuel content (weight %)	
Moisture	47,9
Ash (dry)	2,7

Heating value (MJ/kg)	
HHV (dry, ash free)	21,2
HHV (as delivered)	10,7
LHV (dry, ash free)	19,9
LHV (as delivered)	8,9

Elemental analysis (% dry, ash free)	
C (carbon)	53,1
H (hydrogen)	6,0
O (oxygen)	40,6
S (sulphur)	0,04
N (nitrogen)	0,31
Cl (chlorine)	0,02

When the biomass enters the plant, it is first mechanically dewatered to an MC of 40% and then dried from an MC of 40% to an MC of 15% in a drum dryer. The mechanical dewatering requires an electrical power of 325 kW, as shown in Figure 2, and the wastewater resulting from this process is sent for wastewater treatment. In the drum dryer, hot water is led through pipes in proximity to the biomass, which heats the biomass via conduction and convection. As the biomass is heated, moisture in the biomass is picked up by air, which is blown through the dryer. The humid air is led to a dust scrubber where potential pollutants are captured in the scrubbing water, which is sent for wastewater treatment. The hot water needed for drying is supplied by the district heating heat exchanger in the plant. After the two drying processes, biomass is sent to a furnace for pyrolyzation.

2.3 Pyrolysis

Pyrolysis of biomass is a thermochemical process where biomass is heated to a temperature of typically around 350-700 °C in the absence of oxygen (Brassard et al., 2016). When biomass is pyrolyzed, three products are produced, namely biochar, a non-condensable gas, and a condensable gas (which, if condensed, is often referred to as bio-oil) (Dhyani and Bhaskar, 2018). Pyrolysis of biomass, including condensing of pyrolysis gas, which consists of condensable and non-condensable gas, is illustrated in Figure 4. The biomass pyrolysis process is complex and the respective yield and composition of the three products vary depending on a magnitude of parameters. These parameters include, but are not limited to, biomass type, biomass pre-treatment, reaction temperature, heating rate, and residence time (Kan et al., 2016).

In order to maximise the yield of biochar, "slow" pyrolysis is the preferred pyrolysis process. Slow pyrolysis is defined as having a low reaction temperature, slow heating rate, and long residence time (Dhyani and Bhaskar, 2018). Crombie and Mašek (2014) showed that in a slow pyrolysis system, the energy content in the non-condensable gas is enough for heating and thus sustaining the pyrolysis process, which frees up the use of the condensable gas and biochar for other purposes. As mentioned previously, biochar can then be used to improve soil and sequester carbon while the remaining pyrolysis gas can be used as a combustible for CHP production.

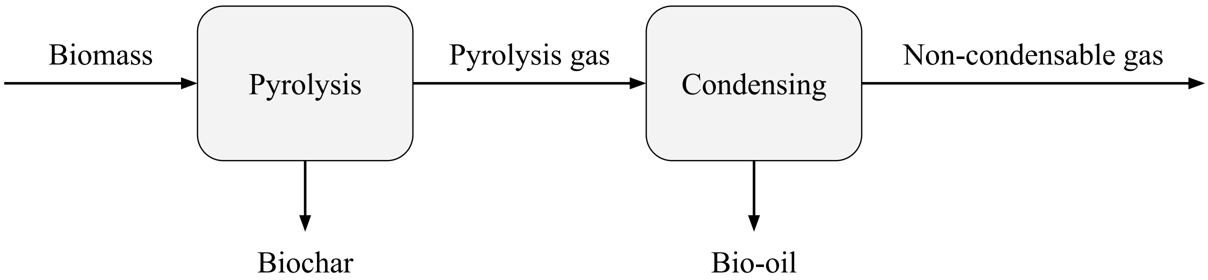

Figure 4. Pyrolysis of biomass including condensing of pyrolysis gas.

In the model of a combined pyrolysis and CHP plant, pyrolysis of biomass takes place in a Rotary Hearth Furnace (RHF), which was originally developed and used for calcination of coal and petroleum coke (Barraclough, 2018). Calcination can be defined as the "process of heating a substance under controlled temperature and in a controlled environment" (Kaur and Bhattacharya, 2011, p.245). An RHF consists of a disk-type hearth, which is slightly tilted inwards and that slowly rotates around a soaking pit. The material that is to be heated in the RHF enters from a feed bin at the outer diameter of the hearth and slowly rotates along the hearth in concentric circles. After a full rotation, angled rabble arms, which are fastened at the roof of the RHF, push the material into the next concentric path, just a bit towards a soaking pit. This procedure is repeated until the material is pushed down and discharged into the soaking pit at the centre of the rotating disk. A top view and a cross-sectional view of an RHF is illustrated in Figure 5. For further explanations of the mechanisms of the RHF, the following sources are recommended: Barraclough, 2018; Brandt, 1986; Edwards, 2015; Ellis and Paul, 2000; Harp, 2017; Predel, 2014; Ragan and Marsh, 1983.

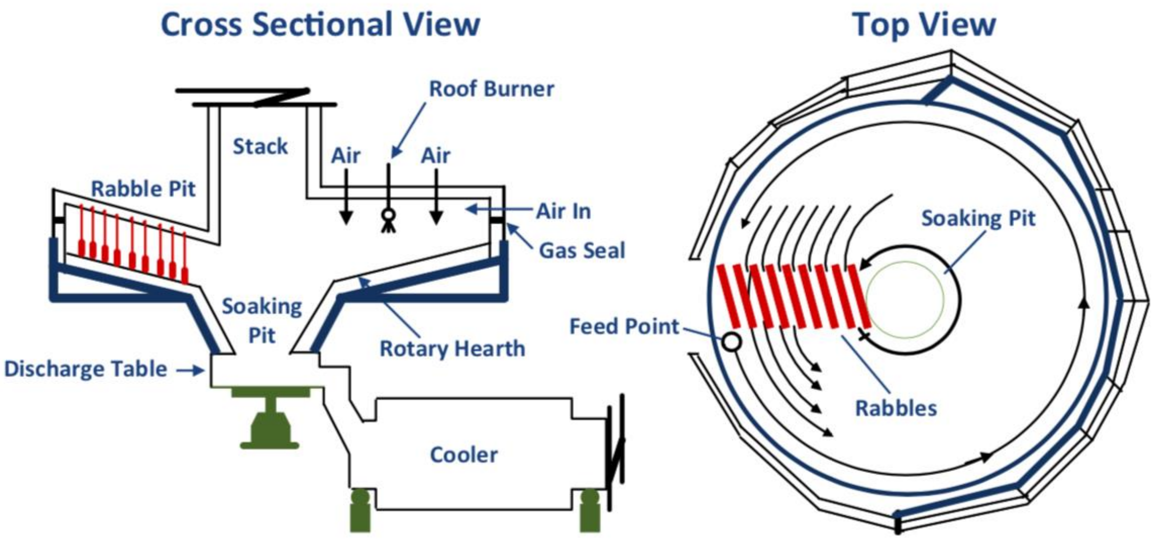

Figure 5. Cross-sectional view and top view of an RHF (Edwards, 2015).

When green or raw coke is calcined in an RHF, the heat needed for calcination is provided by combustion of volatile matters released from the coke during the calcining process (Barraclough, 2018; Brandt, 1986; Ellis and Paul, 2000; Ragan and Marsh, 1983). Sufficient air enters via the roof of the RHF for combustion of volatile matters (Brandt, 1986; Ragan and Marsh, 1983). Barraclough (2018) explains that in some circumstances, the burning of all volatiles released by the coke may result in an overheating of the furnace. To prevent this, he writes that the RHF can be operated in sub-stoichiometric mode. This means that some of the volatile matters are left uncombusted until they reach the flue, where air is introduced in an afterburner to ensure full combustion. When all volatile matters have been combusted, the hot flue gas enters a heat recovery system, which can be used to produce steam and preheat air for the RHF (Barraclough, 2018; Harp, 2017).

An important feature of the rabble arms is that the substance in the RHF is gently stirred, which improves heat transfer and ensures that all the material reaches the desired temperature (Barraclough, 2018; Brandt, 1986; Ellis and Paul, 2000; Ragan and Marsh, 1983). Once the material is discharged from the hearth, it is maintained in the soaking pit for about 15-20 minutes (Barraclough, 2018) to establish thermal equilibrium and ensure that the material has consistent properties (Barraclough, 2018; Brandt, 1986). The soaking pit also functions as a closed valve to prevent air from entering the furnace (Barraclough, 2018; Brandt, 1986). The residence time in the RHF is usually around one hour (Ragan and Marsh, 1983), but can be controlled by adjusting the rotational speed of the disk (Ellis and Paul, 2000).

In the model of a combined pyrolysis and CHP plant, biomass, with an MC of 15%, enters at the feed point of the RHF. It is slowly heated to a temperature of 800 °C with a residence time of one hour, thus producing biochar and pyrolysis gas. The relatively high temperature and long residence time are primarily chosen as these process conditions have been proven to function in RHFs for pyrolysis of lignite coke (Harp, 2017). The biochar is collected in a soaking pit where it is homogenised to obtain consistent properties while at the same time acting as a closed valve to prevent ambient air from entering the RHF. The biochar production capacity of the plant is about 2,5 tonne biochar/hour.

The pyrolysis gas generated in the pyrolysis-process is partially combusted at the roof of the RHF by letting a controlled amount of ambient air mix with the pyrolysis gas. The amount of air supplied at the roof of the RHF is determined so as the temperature in the RHF is maintained at 800 °C. The flue gas resulting from combustion of partially pyrolysis gas is, together with the uncombusted pyrolysis gas, led to an afterburner where the pyrolysis gas is fully combusted and thereafter led to a heat recovery system where steam is produced. The afterburner and heat recovery system are further explained in chapter 2.4. In Figure 6, the pyrolysis process in the RHF is illustrated in greater detail, and in Figure 7, partial combustion of the pyrolysis gas at the roof of the RHF is illustrated.

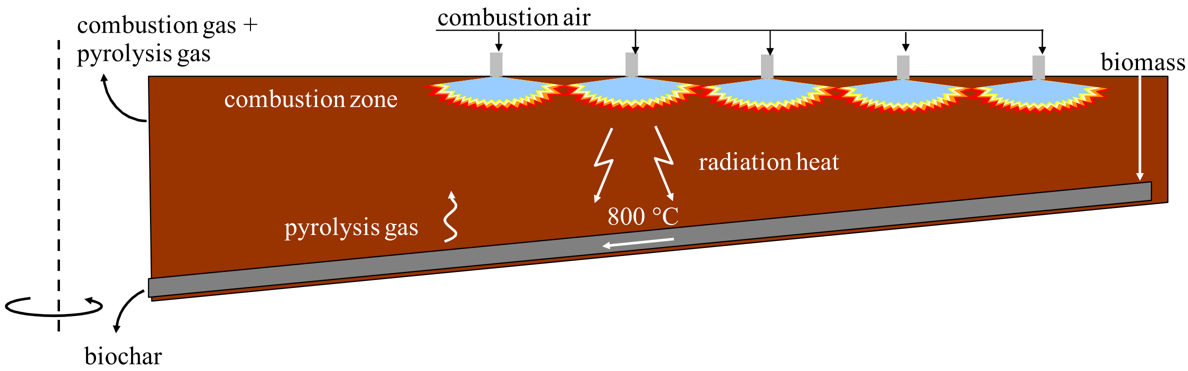

Figure 6. Illustration of the pyrolysis process in the RHF.

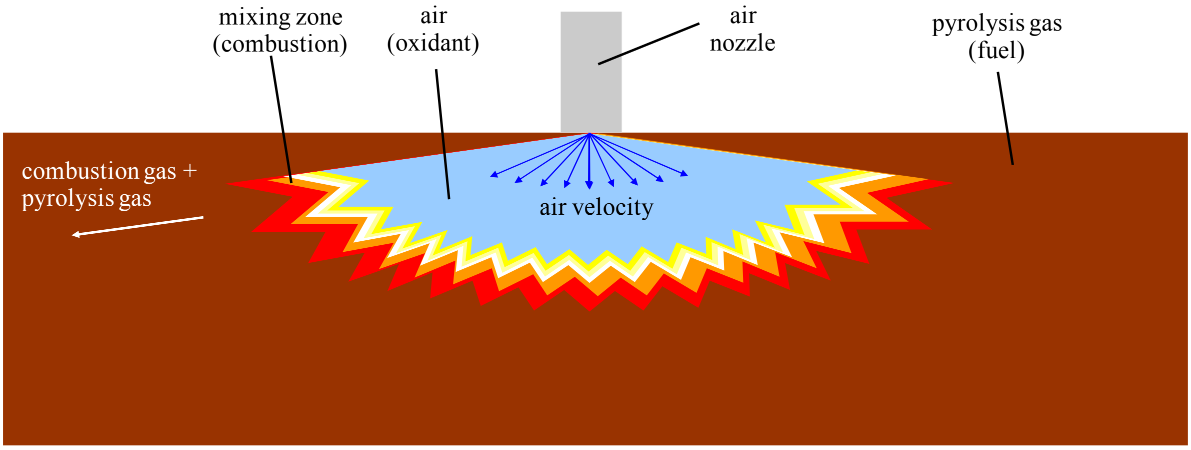

Figure 7. Illustration of partial combustion of pyrolysis gas at the roof of the RHF.

2.4 CHP production

CHP production is the simultaneous generation of electricity and heat from a single energy source (Breeze, 2018; Kerr, 2008; Thorin et al., 2015). Breeze (2018) writes that CHP production is usually centred around a heat engine (i.e. an engine that transforms heat into mechanical energy), such as a steam turbine or a gas turbine, to generate electricity. However, a fundamental aspect of CHP production is to ensure that there is a demand for heat in proximity to the CHP production (Breeze, 2018; Knowles, 2011). As heat cannot be transported as efficiently as electricity, it is essential that a local demand for heat exists (Breeze, 2018), and that the CHP production is designed to meet this demand (Kerr, 2008). The heat demand can, for instance, exist in a district heating network (Thorin et al., 2015), where a central unit, such as a CHP plant, supplies several customers with heating via a distribution network consisting of insulated pipes that transport water (El Bassam et al., 2013). An energy source utilised for CHP production can be waste heat in the form of hot flue gases from a gas turbine (Breeze, 2018; Persson and Olsson, 2002; Thorin et al., 2015), or from combustion of pyrolysis gas. In a system where hot flue gases are used for CHP production, the hot flue gases enter a heat exchanger called heat recovery steam generator (HRSG), where steam is generated (Persson and Olsson, 2002). The steam is then utilised in a steam turbine to generate electricity and afterwards the steam is condensed to supply heat (Breeze, 2018; Persson and Olsson, 2002).

In Sweden, there are about 500 DH systems and all major cities and towns have a DH system in place (Werner, 2017). Additionally, biomass CHP production in Sweden is eligible for electricity certificates, a market-based support system aiming to increase renewable electricity production (The Swedish Energy Agency, 2014). For each MWh electricity produced, a producer obtains an electricity certificate that can be sold to an actor who is required to purchase a certain amount of electricity certificates, based on the actor's electricity sales or consumption (The Swedish Energy Agency, 2014).

In the model of a combined pyrolysis and CHP plant, the uncombusted pyrolysis gas, together with the hot flue gases, are led to an HRSG. Before the gases enter the HRSG, a burner array equipped with air nozzles is used, which mixes the surplus pyrolysis gas with air, to ensure full combustion of the pyrolysis gas. The hot flue gases then enter the HRSG to generate superheated steam in an HRSG. The HRSG is equipped with heat pick-up tubes consisting of a superheater, a steam drum, and an economizer. After the flue gas has passed the economizer, it is led to a stack. The steam generated in the HRSG is used in a steam turbine to generate mechanical energy. The mechanical energy is then converted to electricity by a generator, and the electric power output is 5,3 MW, as seen in Figure 3. The steam is thereafter led to a condenser to generate district heating. The steam from the steam turbine is condensed with the help of a district heating network. The temperature of cold incoming water from the DH network is assumed to be 35 °C, and warm outgoing water to the DH network is assumed to be 115 °C. The heat supplied to the district heating network is 14,4 MW, as seen in Figure 3. Some of the generated heat is used in the drum dryer to dry biomass.

2.5 Biochar

Biochar is a term subjected to confusion as scholars use it in different ways and often interchange the term biochar with char and charcoal. In this thesis, biochar is defined as "the solid product of pyrolysis, designed to be used for environmental management" (Lehmann and Joseph, 2015, p.2). Biochar has been reported to have simultaneous benefits when mixed in soil. On one hand, biochar acts as a soil amendment, and on the other hand, it acts as a way of sequestering carbon in the ground. Multiple studies confirm that when biochar is used in soils, it can have an agronomic value as it improves water retention ability, nutrient uptake, and crop yield increases (Brassard et al., 2016). However, the agronomic value of biochar is dependent on not just the biochar quality, but also the climate and soil type (Campbell et al., 2018; Lehmann and Joseph, 2015). More research in a Swedish context is needed to quantify the agronomic value of biochar in Sweden (Avfall Sverige, 2018).

When biochar is used in soils, it also functions as a carbon sink. Biochar is able to store carbon in the ground which the biomass has accumulated during its lifetime through photosynthesis, as opposed to the carbon being released back to the atmosphere as carbon dioxide when biomass naturally degrades (Jirka and Tomlinson, 2014; Lehmann, 2007). Thus, the production of biochar is able to remove carbon dioxide from the atmosphere by prolonging the carbon cycle and mitigate global climate change (Qambrani et al., 2017). According to Daoson et al. (2020), biochar, through the use as a soil enhancement product, is a technology that has the second largest potential for CDR in Sweden, with Carbon Capture and Storage (CCS) technologies having the largest potential.

Apart from using biochar as a soil enhancement product, several other applications, such as using biochar as a water filtration media (Krishna et al., 2014; Li et al., 2016), as a filler in concrete (Cuthbertson et al., 2019; Gupta and Kua, 2017) or as animal feeding (Schmidt et al., 2019), have been investigated in literature. However, the application of biochar as a soil amendment is still the most researched application of biochar, and the market of biochar as a soil amendment product is the most prominent market of biochar in Sweden (Avfall Sverige, 2018).

2.5.1 Density

An essential property of biochar is its density, which can be measured either as solid density or as bulk density. Solid density is the "true" density of biochar and represents the density of biochar on a molecular level while bulk density, or "apparent" density, represents the density of a larger volume of biochar particles (Lehmann and Joseph, 2015). Bulk density is a parameter that buyers of biochar are interested in to evaluate how much biochar is purchased (Brewer and Levine, 2015). It is also a parameter required to be stated by producers of biochar to obtain the European Biochar Certificate (EBC) (the EBC is further explained in chapter 2.5.2). The bulk density of biochar is also an essential parameter for the production of biochar to properly dimension the containers needed for storing biochar (Guo et al., 2020). Lehmann and Joseph

(2015) write that typical values of biochar bulk density are around 0,09 Mg/m^3 to 0,50 Mg/m^3. They also write that there is a linear relationship between biochar bulk density and feedstock wood bulk density, which follows equation 1.

$$Biochar\ bulk\ density = 0{,}8176 * wood\ bulk\ density \tag{1}$$

2.5.2 Quality standards

Due to biochar being a relatively new approach of both sequestering carbon and improving soils, there is no official legislation for the production or use of biochar. However, voluntary biochar quality standards exist, where three of the most well recognised are the European Biochar Certificate (EBC) in Europe, the Biochar Quality Mandate (BQM) in the United Kingdom and the International Biochar Initiative Biochar Standards (IBI-BS) in the United States (Meyer et al., 2017). From a Swedish context, the EBC is the most relevant quality standard for biochar. The EBC was established by biochar scientists with the aim of serving as the industrial standard for biochar in Europe and to reduce the risks for hazard of health and environment, both in the production and use of biochar (EBC, 2013). The EBC defines biochar as "a heterogeneous substance rich in aromatic carbon and minerals. It is produced by pyrolysis of sustainably obtained biomass under controlled conditions with clean technology and is used for any purpose that does not involve its rapid mineralisation to CO_2 and may eventually become a soil amendment" (EBC, 2012, p.6). To be approved by the EBC, several requirements need to be fulfilled. These include requirements on the biomass feedstock used to produce biochar, keeping records of the biochar production, sampling of biochar, requirement of biochar properties, requirements for the pyrolysis process and health, and safety regulations (EBC, 2012).

2.5.3 Market

The use of biochar as a soil improvement product is the most widely accepted market for biochar (Jirka and Tomlinson, 2014) and the most likely application of biochar in Sweden in the near future (Avfall Sverige, 2018). However, the price of biochar is far from established as no major industrial market of biochar exists (Dickinson et al., 2015). There is a wide range of biochar prices in literature, as can be seen in Table 2.

A reason why the price of biochar varies so much in literature could be, as mentioned in chapter 2.5, that the agronomic value is difficult to estimate. The agronomic value is dependent on a multitude of parameters, such as type of feedstock, pyrolysis temperature and soil type, and, as no official legislative framework of the production or use of biochar is in place to create a consistency of these parameters, there seems to be a lack of shared understanding of the agronomic value of biochar in different locations.

Apart from the agronomic value, there could be an economic value in terms of carbon sequestration potential of biochar mixed in soil through carbon markets or governmental support. Currently, biochar is not eligible for any carbon credits as, among other things, it is difficult to determine the stability of carbon in biochar in soils, meaning that it is difficult to predict the actual amount of carbon sequestered (Shackley et al., 2016). Only a fraction of the carbon in freshly produced biochar is contained in the biochar for a longer period of time, which must be accounted for in a potential carbon market (Sohi et al., 2010). Bach et al. (2016) writes that carbon credits will most likely be based on the half-life of biochar and that, based on the research that exists today, the median half-life of biochar in soils is proven to be about 20 years.

Table 2. Biochar prices in literature.

Price of biochar	**Notes**	**Source**
Varies between 855 SEK$_{\$}$/tonne and 84 075 SEK$_{\$}$/tonne with an average of 25 175 SEK$_{\$}$ /tonne	Global price for pure biochar based on results from a survey with companies selling biochar, excluding any distribution costs and value-added tax (VAT). Does not take into consideration whether the price is at retail or wholesale.	(Jirka and Tomlinson, 2014)
19 600 SEK$_{\$}$/tonne	Average wholesale price.	(IBI, 2014)
9804 SEK$_{\$}$/tonne	Average price in USA.	(Groot et al., 2018)
Varies between 5700 SEK$_{\$}$/tonne and 11 400 SEK$_{\$}$/tonne	Price at factory gate (i.e. wholesale price) in Europe.	(Lehmann and Joseph, 2015)
Between 2600 SEK/m^3 and 3000 SEK/m^3	Based on the willingness to pay for biochar among soil manufacturers in Sweden.	(Avfall Sverige, 2018)
Between 7420 SEK$_{€}$/tonne and 8480 SEK$_{€}$/tonne	Price in Finland.	(Salo, 2018)
6400 SEK$_{€}$/tonne	Wholesale price in the European Union in 2016.	(Meyer et al., 2017)
Between 950 SEK$_{\$}$/tonne and 3800 SEK$_{\$}$/tonne for pyrolysis temperature <750 °C or between 4750 SEK$_{\$}$/tonne and 6650 SEK$_{\$}$/tonne for pyrolysis temperature >750 °C	Assumed selling price of biochar based on feedback from local Australian biochar producers.	(Patel et al., 2019)
Minimum of 675 SEK$_{\$}$/tonne and maximum of 23 864 SEK$_{\$}$/tonne	The minimum price is based on the value of the energy content in biochar compared to the price and energy content of coal. The maximum price is based on the highest average price of biochar found in literature.	(Campbell et al., 2018)

Based on a median half-life of 20 years and a time horizon of 100 years, which is commonly used when evaluating GHG offset potential, about 13% of the carbon in freshly produced biochar can be accounted for as sequestered carbon when biochar is mixed in soil (Bach et al., 2016). Thus, the actual amount of carbon sequestered in biochar containing 1 kg of carbon would be 0,13 kg. However, it is not uncommon in literature to expect a longer mean residence time of carbon in biochar mixed in soil and, consequently, assume a higher fraction of the carbon content being sequestered on a 100-year time horizon. In a study by Hammond et al. (2011), it is assumed that the carbon in biochar consists of 85% stable carbon and 15% unstable carbon and that the mean residence time of the stable carbon is 500 years. The unstable carbon does not contribute to long term carbon sequestration and, thus, the fraction of carbon in freshly produced biochar considered as sequestered on a 100-year timescale is assumed to be 68% (Hammond et al., 2011). Lehmann and Joseph (2015) write that the mean residence time of different types of biochar vary greatly and found that the mean residence time of biochar in literature ranges between 6 and 4419 years. Thus, if carbon credits are to be given to biochar, it must be considered that different types of biochar have different carbon sequestration potentials.

In the model of combined pyrolysis and CHP plant, one kg of biochar contains about 0,909 kg carbon. No information regarding the mean residence time of the produced biochar in soils is provided as it would most likely also depend on the soil conditions. However, as the pyrolysis temperature is relatively high, it is plausible to believe that the biochar produced in the plant would be of high quality in terms of high surface area (Tomczyk et al., 2020), and high fixed carbon content (Sun et al., 2017).

Although no carbon markets exist for biochar, governmental support for investments in biochar production plants exist in Sweden through a fund called Klimatklivet (Daoson et al., 2020). Grants from Klimatklivet are given with the purpose of achieving the most significant climate benefit per invested Swedish krona. Currently, the average emission decrease for each invested Swedish krona by the fund is 2,18 kg of carbon dioxide equivalents (Naturvårdsverket, 2020). This means that for each Swedish krona invested by Klimatklivet, they can expect an emission decrease of 2,81 kg CO_2e.

2.6 Plant economics

Evaluating whether a plant, of any kind, should be built or not requires the economy of the plant to be analysed. In this chapter, literature regarding the costs of constructing and operating CHP and chemical manufacturing plants are reviewed, divided into Capital Expenditures (CapEx), Operational Expenditures (OpEx), and non-operational expenditures. The costs of chemical manufacturing plants are reviewed to provide a foundation for the costs of the pyrolysis part of the combined pyrolysis and CHP plant. Literature regarding plant financing is also reviewed.

2.6.1 CapEx

CapEx refers to the expenditures required for preparing a plant for operation and can be defined as "the total amount of money needed to supply the necessary plant and manufacturing facilities plus the amount of money required as working capital for operation of the facilities" (Peters and Timmerhaus, 1991, p.166). Included in the CapEx are the funds needed to purchase land, equipment, and buildings as well as the funds needed to design or perform associated modifications of an existing plant to bring the plant into operation (Couper, 2003).

The CapEx of a plant can be estimated based on more or less reliable data. According to Humphreys (2005), three sources of data can be used when estimating the CapEx, namely internal company data from similar project costs, proprietary cost data obtained from suppliers, or publicly published cost information. Public data is not to be preferred since the accuracy level is unclear, and the source might not be indicated. It may also be ambiguous whether purchased or installed costs are presented. Additionally, public data may not include information about when it is dated or about cost index values, making it further unreliable to use as a base for estimations of CapEx (Couper, 2003). Proprietary cost data obtained from suppliers are the best source of data as this is the actual cost that would incur if a plant was constructed. If cost data exists for a similar plant but with a different size than desired, size factoring exponents can account for this difference. These are reviewed in chapter 2.5.1.4. Indexes for inflation can also be used to adjust historical data to better correspond with present values or to assess future costs. These indexes are reviewed in chapter 2.6.1.5.

The CapEx are normally divided into two subcategories: Fixed Capital Investment (FCI) and working capital (Humphreys, 2005; Peters and Timmerhaus, 1991; Towler and Sinnott, 2013; Winter, 1969). The FCI can be defined as the one-time cost for all the facilities needed for the plant (Humphreys, 2005), and working capital is the funds needed for the plant to function operationally on a day-to-day basis (Perry and Green, 2008).

2.6.1.1 Fixed Capital Investment

The FCI is usually the main component of the CapEx, and other components, such as working capital or land cost, are often either derived from or included in the FCI. There are several approaches to break down the FCI in smaller components, and below is an overview of how different scholars describe the FCI in relation to CapEx.

According to Towler and Sinnott (2013), the FCI can be divided into inside battery limits (ISBL), offsite battery limits (OSBL), engineering and construction costs, and contingency charges. The ISBL plant cost includes procurement and installation of all process equipment that make up the new plant. The ISBL can further be divided into direct field costs and indirect field costs. The OSBL constitutes all additional changes needed for site infrastructure to match the plant. OSBL investments usually include interactions with utility companies such as suppliers of water and electricity. The engineering costs (also called home office costs or contractor charges) are the detailed design and engineering services that need to be done to execute the project. Contingency charges act as a buffer to the project, thus allowing for higher cost variations. According to Towler and Sinnott (2013), the FCI can be estimated by first investigating the ISBL costs and thereafter calculating the remaining major cost components as percentages of it. Early in the project, it is crucial to define ISBL costs carefully as they serve as the basis for estimating the other costs. The OSBL costs are usually within the range of 10-100 % of ISBL costs, depending on project scope and the infrastructure requirements. Engineering costs are normally estimated between 10-30% of ISBL plus OSBL costs depending on the size of the project where the portion decreases as the project grows. The contingency charge should be a minimum of 10 % of ISBL plus OSBL but up to 50% if the technology is uncertain.

Peters and Timmerhaus (1991) propose a similar breakdown of the FCI as the one above by Towler and Sinnott (2013). Peters and Timmerhaus (1991) divide the FCI into manufacturing FCI and non-manufacturing FCI. The former is the capital needed for the installed process equipment with all auxiliaries required for process operation, including site preparation. The latter is the construction overhead capital and the capital needed for components that are not directly part of the process operation. Non-process operation components include land, processing buildings, administrative and other offices, warehouses, laboratories, facilities for transportation and shipping, utility and waste-disposal facilities, shops, and other parts that are permanent to the plant. Construction overhead capital includes the costs for field-office, supervision expenses, home-office expenses, engineering expenses, miscellaneous construction costs, contractor's fees and contingencies. Start-up expenses can be represented as a one-time-only expenditure in the overall cost analysis in the first year of operation or as a part of the total capital investment. Peters and Timmerhaus (1991) also present an overview of the cost components of the FCI, which is shown in Table 3.

Table 3. Overview of cost components in FCI (Peters and Timmerhaus, 1991).

Component	**Direct or indirect cost**	**% of FCI**
Purchased equipment	Direct	15-40
Purchased equipment, installation	Direct	6-14
Instrumentation and control (installed)	Direct	2-8
Piping (installed)	Direct	3-20
Electrical (installed)	Direct	2-10
Buildings (including services)	Direct	3-18
Yard improvement	Direct	2-5
Service facilities (installed)	Direct	8-20
Land	Direct	1-2
Engineering and supervision	Indirect	4-21
Construction expense	Indirect	4-16
Contractor's fee	Indirect	2-6
Contingency	Indirect	5-15

Couper (2003) describes the FCI solely as "fixed" to the land, i.e. the part of the total capital investment pertinent to the manufacturing of the product. According to his definition, the other components of the total capital investment include land, offsite capital (utilities and services), allocated capital, working capital, start-up expenses, and other capital items. These components are thus, in contrast to the definition of Peters and Timmerhaus (1991) and Towler and Sinnott (2013), not part of the FCI. Couper (2003) proposes the following percentages to calculate the components of the CapEx. The cost of land makes up 3% of the FCI. The contingency charges are divided into a project contingency of 15-20% if the process information is fixed, and an additional process contingency cost of 15-20% if the process information is not fixed. If the plant in question is a greenfield or grass-root plant, the offsite capital can be estimated to 40-150% of the Ex Works process equipment cost.

Start-up expenses, according to Couper (2003), incur from the end of the plant construction to the point in time when products are produced in the quality and quantity desired. The start-up expenses include “operator and maintenance employee training, temporary construction, auxiliary services, testing and adjustment of equipment, piping and instruments etc” (Couper, 2003, p.114). Couper (2003) refers to Baasel (1976) and Peters and Timmerhaus (1991) for estimations of the start-up expenses, where Baasel (1976) suggests the expenses are estimated as 5-20% of the FCI and Peters and Timmerhaus (1991) suggest 8-10% of the FCI.

Humphreys (2005) defines the FCI as the one-time cost for all the facilities needed for the plant. In the FCI, he include costs for land, design, engineering, equipment, utilities, freight, and plant start-up, among other components. Winter (1969) explains FCI as the investment in production and auxiliary facilities. As the main components, he puts forward “purchased equipment, equipment installation, foundations, piping, instrumentation, insulation, electricity, buildings, painting, land and yard improvements, utilities, physical plant cost for engineering and construction, start-up expenses, and direct plant cost for contractor’s fee and contingency” (p.46). Garrett (1989) divides the components of a plant cost estimate into on-site facilities, installation costs, construction expenses, company costs, off-site facilities, start-up, and working capital. The cost for acquiring land can be included in the FCI (Humphreys, 2005) or be left out since it can be considered non-depreciable (Couper, 2003).

Although scholars have a diverging view of what should be included in the FCI, it is common to estimate the FCI based on the cost of major process equipment in the plant. Using cost data of the equipment in a plant, a cost estimation of the FCI can be conducted by applying factors and percentages on non-equipment costs. Therefore, it is essential to have as accurate equipment cost data as possible. The most essential factors when determining whether cost data is accurate or not, are the source from where the data is obtained, the basis, the date, potential errors and the range over which the cost data apply. It is also important to consider what is included in the presented cost data from a source. Three main classifications are commonly used for presenting cost data, namely purchased, delivered, and installed cost (Couper, 2003). The purchased cost is the cost of equipment at the plant of the manufacturer, also called Ex Works. The delivered cost is the purchased cost, including delivery charges. The installed cost of equipment is the cost of equipment, which has been delivered and set in place in the plant. However, it does not include costs for piping, electrical integration, or insulation.

The most accurate cost data of a piece of equipment is obtained directly from a suitable vendor (Couper, 2003; Garrett, 1989), and the second most accurate alternative is to use cost data from similar equipment that has previously been purchased (Bailie et al., 2018). A third method, which can be used for preliminary cost estimates, is to utilise summary graphs available for different types of common equipment. This cost data must, however, be adjusted for differences in unit capacity and for inflation, which is reviewed in chapter 2.6.1.4 and 2.6.1.5, respectively.

2.6.1.2 Working capital

Working capital is the funds a company must contribute to a project to commence operation of a plant and meet obligations that are due (Humphreys, 2005). Working capital is a crucial aspect of plant operation, in particular for unproven processes and novel products (Couper, 2003). It is tied up in inventories, products, and cash needed for transfers to suppliers and customers. The working capital is bound in the investment during its lifespan and is recovered once the plant is shut down. It is, therefore, not considered depreciable. There are two main methods of estimating the working capital for a new project, the percentage method and the inventory method. The former is calculated as a percentage of the FCI or total capital investment, and the latter is estimated based on the cost of production (Couper, 2003). None of the methods are standardised and there exist several breakdowns of both since their functionality depends highly on the production facility in question. Below are explanations of some of the ways to conduct the estimation of working capital.

If working capital is calculated as a percentage of the capital investment, different percentages can be used. Peters and Timmerhaus (1991) write that an initial working capital amounts to 10-20% for most chemical plants. According to Winter (1969), the working capital amounts to 10-15% of the FCI or 25% of the annual product sales volume. Humphreys (2005) sets the working capital to 10-20% of the FCI, or approximately 25% of operating costs in the majority of manufacturing industries. Towler and Sinnott (2013) state that the working capital can vary between 5-30% of the FCI, and that it increases with the production's complexity and with a diverse range of products. Couper (2003) proposes the working capital to amount to 15-25% of the total capital investment if a product is manufactured and sold at a uniform yearly rate.

If working capital is calculated using an inventory method, the value for different inventories are used as a basis. The working capital can, for example, consist of money invested in raw material and stock supply, finished products in stock and semi-finished products, accounts receivable, cash on hand for monthly payments of operating expenses, accounts payable, and taxes payable (Peters and Timmerhaus, 1991). Alternatively, it could consist of the value of raw material inventory, value of product and by-product inventory, cash on hand, accounts receivable, credit for accounts payable, and spare parts inventory (Towler and Sinnott, 2013).

2.6.1.3 Size factoring exponents

Size factoring exponents are used to calculate the cost for a plant or piece of equipment with a desired capacity or size by using the known cost for a similar plant or piece of equipment, but with different capacity or size. The calculation is done using equation 2, which is often referred to as the 7/10ths rule or the 6/10ths rule because the average value for the exponent is 0.7 for new plants and 0.6 for new equipment. The exponent varies between 0.4 and 0.8 for most process equipment, with an average value of 0.6 (Couper, 2003). However, the values for exponents are highly dependent on what kind of plant or piece of equipment is considered and should, therefore, be adjusted to suit each specific case.

$$C_2 = C_1 * \left(\frac{Q_2}{Q_1}\right)^x \quad (2)$$

where:
$C_2 = desired\ cost\ of\ capacity\ Q_2$
$C_1 = \ cost\ of\ capacity\ Q_1$
$x = cost\ capacity\ factor$

Exponent tables for some common pieces of equipment have been compiled by various authors, such as by Couper (2003), which is shown in Table 4.

Table 4. Cost capacity exponents for different equipment groups (Couper, 2003).

Equipment group	**Average exponent**
General equipment	0,68
Heat exchange equipment	0,68
Fluid-moving equipment	0,63
Tanks, vessels, and towers	0,63
Environmental equipment	0,82

2.6.1.4 Equipment and inflation cost indexes

According to Humphreys (2005), there are three main reasons why costs change continuously: technology change, change in availability of labour and material, and change of value of the monetary unit, i.e. inflation. Therefore, the cost of a plant or piece of equipment differs depending on the time of its purchase. A fair amount of inflation cost indicators has been devised to be used to estimate how costs for materials, supplies, and equipment change each year. The main indexes for process industries are: Chemical Engineering Plant Cost Index (CEPCI), Marshall and Swift Cost Index, Intratec Chemical Plant Construction Index and Nelson-Farrar Indexes, of which the CEPCI is the most comprehensive. The CEPCI is published monthly and is based on data from the U.S. Bureau of Labor Statistics. Its index values aim at reflecting the mix of services and goods that are associated with industries within chemical processes and it can be considered analogue to the consumer price index (CPI) (Bailie et al., 2018). The CEPCI consists of four major components that are weighted by a percentage to their influence on the total index. The components are equipment, machinery and support (61%), erection and installation labour (22%), buildings, materials and labour (7%), and engineering and supervision (10%) (Couper, 2003). Furthermore, the CEPCI has elaborated indexes specifically for cost categories such as equipment, labour, and material.

2.6.1.5 Overview of CapEx for pyrolysis plants

Although the slow pyrolysis technology is far from mainstream, and it is difficult to properly evaluate the capital costs for pyrolysis plants some literature presents capital costs for pyrolysis plants. This is illustrated in Table 5. However, in some sources, it is difficult to interpret if all components of the CapEx are included in the figure presented or not and, if not, which parts of the CapEx are included.

Table 5. Capital costs for different pyrolysis plants.

Host organisation	Investment cost	Input biomass	Annual capacity	Configuration	Source
Fortum/Valmet	318 million SEK$_{€}$	450, 000 solid cubic meter wood annually	50 000 tonnes bio-oil	Fast pyrolysis unit integrated in existing CHP plant	Fortum (2013)
AE Côte-Nord	681 million SEK$_{\$}$	72,000 of oven dry tonnes forestry mill white wood residuals and forestry waste materials annually	42 M litres bio-oil	Fast pyrolysis	Kelly Sears Consulting Group (2017)
Twence/Empyro	212 million SEK$_{€}$ (a)	5 tonnes per hour of woody biomass (b)	24 000 tonnes crude flash pyrolysis oil (a)	Flash pyrolysis (a)	a) LSB (n.d.) b) Bioenergy International (2015)

2.6.1.6 Overview of CapEx for CHP plants

The capital costs for CHP plants are usually based on the electrical power output of the CHP plant. In Table 6, the specific CapEx for different CHP configurations is shown.

Table 6. Specific investment cost for CHP plants.

CHP configuration	Specific CapEx	Source
Biomass CHP plant	55 100 SEK$_{\$}$/kW$_e$	(Breeze, 2018)
Steam turbine CHP	>19 000 SEK$_{\$}$/kW$_e$	(Breeze, 2018)
Biomass CHP and power plants with capacity of up to 50 MW$_e$	Between 28 500 SEK$_{\$}$/kW$_e$ and 57 000 SEK$_{\$}$/kW$_e$	(Paul, 2010)
Biomass CHP	16 625 SEK$_{\$}$/kW$_e$	Thorin et al., 2015)
Biofuel based steam turbine with steam generator	19 100 SEK/kW$_e$	(Persson and Olsson, 2002)
Gas turbine with HRSG	>3000 SEK/kW$_e$	(Persson and Olsson, 2002)
Biomass CHP 5 MW$_e$	53 900 SEK/kW$_e$	(Nohlgren et al., 2014)
CHP (all types)	27 800 SEK$_{\$}$/kW$_e$ (median) 43 000 SEK$_{\$}$/kW$_e$ (mean)	(Wittenstein and Rothwell, 2015)

2.6.2 OpEx

OpEx refers to the expenditures incurred during plant operation and has historically received less attention in literature compared to CapEx (Couper, 2003; Perry and Green, 2008). The OpEx is nonetheless a vital part for evaluating the profitability of a plant (Couper, 2003; Garrett, 1989; Humphreys, 2005; Peters and Timmerhaus, 1991; Towler and Sinnott, 2013). To understand the OpEx, it is important to specify what is meant by the term. Scholars use different terms, such as Operating expense (Couper, 2003; Humphreys, 2005), Total Product Cost (Peters and Timmerhaus, 1991), Manufacturing or Operating Cost (Garrett, 1989; Perry and Green, 2008), and Production Cost (Towler and Sinnott, 2013), to denominate the recurring costs of operating a plant. In this thesis, OpEx is used to denominate the recurring costs incurred when operating a plant, as it will help to clearly distinguish these costs from the CapEx.

OpEx can be presented in multiple ways with different cost-bases. Commonly, one of the following three cost-bases is used; cost per unit, cost per day, or cost per year. The annual cost is often recommended as the best one as it, amongst other things, takes the on-stream time factor of a plant into consideration (i.e. the fraction of time a plant is in operation during a year), and is relatively easy to convert to another cost-base if necessary (Humphreys, 2005; Peters and Timmerhaus, 1991).

OpEx is often divided into different types of costs, such as raw material, operating labour, and maintenance. These expenses can be classified in different ways. Couper (2003) explains two sets of terminologies used for classifying an expense. The first terminology differentiates between direct and indirect expenses. Direct expenses can be directly linked to the manufacturing of a product and tend to vary in proportion to the production rate. Examples of direct expenses are utilities, such as electricity and labour. Indirect expenses do not vary as much or do not vary at all in proportion to the production rate. An example of an indirect expense is depreciation. The second terminology differentiates between variable, fixed and semi-variable expenses. Variable expenses are proportional to the production rate, i.e. when the production rate increases, the variable expenses also increase. Fixed expenses are the opposite of variable expenses, i.e. when the production rate changes, the fixed expenses stay the same. Semi-variable expenses are partly fixed and partly variable. Labour can serve as an example of a semi-variable expense. If the production rate decreases and the need for half of a labourer ceases to exist, the labour expense will most likely stay the same as a fraction of a labourer generally cannot be removed. However, if the production rate decreases even more and the need for one full labourer ceases to exist, it is more likely that an employee will be laid off and the labour expense will decrease.

In CHP plants, OpEx is often divided into three types of expenses: fuel costs, operating and maintenance (O&M) costs, and capital costs (i.e. depreciation and interest) (Colnerud Granström, 2011). Fuel costs are comparable with costs for raw material in manufacturing plants, which is reviewed in chapter 2.7.2.1. O&M costs for CHP plants in Sweden are about 200 SEK/MWh heat and electricity produced (Colnerud Granström, 2011), and the capital costs of depreciation and interest, which are conceptually similar for CHP plants and manufacturing plants, are reviewed in chapter 2.5.3.1 and 2.5.3.2, respectively.

In manufacturing plants, the evaluation of OpEx is not as straightforward as with CHP plants. The largest source of error when estimating OpEx for manufacturing plants is omitting an expense (Winter, 1969). Therefore, it is useful to gather all individual expenses in a table, divided into different categories (Peters and Timmerhaus, 1991). As firms have different accounting practices, the names of these categories and the expenses included in each category differ between companies and in literature. Thus, there is no standard way of categorising expenses (Silla, 2003). However, the most important thing when estimating OpEx is not to categorise expenses in a specific way but, as stated above, not omitting any expense (Silla, 2003). To obtain OpEx for manufacturing plants, individual expenses, such as raw material, and categories of expenses, such as distribution costs, are estimated and added together. Estimation of expenses and categories of expenses can be done in several ways and are explained in the following sections. It should be noted that although the expenses of interest, depreciation and income taxes can be considered to be OpEx, they are not as directly related to the operation of the plant, and are therefore not reviewed in this chapter but instead reviewed in chapter 2.5.3.

2.6.2.1 Raw Material

Raw material, or fuel as it is more commonly called for CHP plants, is usually the largest expense within OpEx for both manufacturing plants (Bailie et al., 2018; Couper, 2003; Humphreys, 2005; Perry and Green, 2008; Towler and Sinnott, 2013), and CHP plants (Abrahamsson and Schrammel, 2016; Ferreira et al., 2014). Therefore, it is essential that this expense is estimated as accurately as possible (Couper, 2003). The raw material required for a plant is typically derived from the plant's material balance (Couper, 2003; Ereev and Patel, 2012; Garrett, 1989; Perry and Green, 2008; Peters and Timmerhaus, 1991). The price for raw material can be obtained from open literature or directly from suppliers (Humphreys, 2005; Towler and Sinnott, 2013), where the latter is preferred if possible as it is often more accurate (Couper, 2003; Ereev and Patel, 2012; Garrett, 1989; Perry and Green, 2008). Purchase prices found in open literature can often be higher than the actual price as companies have the ability to negotiate and bargain with suppliers when purchasing raw materials in large quantities and with a long-term contract (Couper, 2003; Perry and Green, 2008; Towler and Sinnott, 2013). An important aspect to consider when evaluating the expense for raw materials is that prices from literature or suppliers may be expressed excluding transportation which means that an expense for transportation from the supplier to the plant must be added to obtain the raw material expense (Couper, 2003; Garrett, 1989; Humphreys, 2005).

2.6.2.2 Operating labour

The required operating labour for a plant can be evaluated in multiple ways depending on the data available and the purpose of the estimation. Three methods, developed by different authors, for estimating the required operating labour are presented by Ereev and Patel (2012). The first method was developed by Ulrich in the book "A Guide to Chemical Engineering Process Design and Economics" and is based on the type of equipment present in the plant (Ereev and Patel, 2012). For each type of equipment, Ulrich (1984) gives an estimate of how many operators are needed per shift to operate one unit of the equipment. The estimates for different types of equipment are presented in Table 7. The total amount of operators needed for the plant can thus be calculated based on which equipment is used in the plant (Ulrich, 1984).

Table 7. Operator requirements for various types of process equipment (Ulrich, 1984).

Generic equipment type	Operators per Unit per Shift
Auxiliary Facilities	
- Air plants	1
- Boilers	1
- Chimneys or stacks	0
- Cooling towers	1
- Water demineralizers	0,5
- Electric generating plants	3
- Portable electric generating plants	0,5
- Electric substations	0
- Incinerators	2
- Mechanical refrigeration units	0,5
- Wastewater treatment plants	2
- Water treatment plants	2
Conveyors	0,2
Crushers, mills, grinders	0,5-1
Drives and power recovery machines	-
Evaporators	0,3
Vaporizers	0,05
Furnaces	0,5
Gas movers and compressors	
- Fans	0,05
- Blowers and compressors	0,1-0,2
Gas-solids contacting equipment	0,1-0,3
Heat exchangers	0,1
Mixers	0,3
Process vessels	
- Towers (including auxiliary pumps and exchangers)	0,2-0,5
- Drums	-
Pumps	-
Reactors	0,5
Separators	
- Clarifiers and thickeners	0,2
- Centrifugal separators and filters	0,05-0,2
- Cyclones	-
- Bag filters	0,2
- Electrostatic precipitators	0,2
- Rotary and belt filters	0,1
- Plate and frame, shell and leaf filters	1
- Expression equipment	0,2
- Screens	0,05
Size enlargement equipment	0,1-0,3
Storage vessels	-

The second method presented by Ereev and Patel (2012) is based on how many tonnes of end product is manufactured and was suggested by Peters, Timmerhaus and West in the book “Plant design and economics for chemical engineers”. In the fourth edition of the book, Peters and Timmerhaus (1991) explain that, for each tonne of end product manufactured, between 0,33 to 8 employee hours are needed, where the variation between 0,33 and 8 depends on the type of plant. Firstly, for a plant processing fluids, the number of employee hours needed per tonne product is between 0,33 to 2. Secondly, for a solid-fluid processing plant, the number of employee hours needed per tonne product is between 2 to 4. Lastly, for a plant processing solids, such as a coal briquetting plant, the number of employee hours needed per tonne product is between 4 to 8 (Peters and Timmerhaus, 1991).

The third method presented by Ereev and Patel (2012) was developed by Wessel in the article “New graph correlates operating labor data for chemical processes” from 1952, and is based on how many processing steps are present in the plant and on the plant capacity. A processing step is defined as “any unit operation, unit process, or combination thereof, which takes place in one or more units of integrated equipment on a repetitive cycle or continuously, e.g., reaction, distillation, evaporation, drying, filtration, etc.” (Peters and Timmerhaus, 1991, p.200). The amount of processing steps present in a plant can be identified from a flow sheet diagram of the plant (Couper, 2003; Perry and Green, 2008; Peters and Timmerhaus, 1991). Based on the amount of processing steps and the plant capacity, the required operating labour can be estimated as shown in equation 3 (Couper, 2003; Perry and Green, 2008). The method is applicable for a plant producing between 2 to 2000 short tons (i.e. 1,814 to 1814 tonnes) of product per day (Couper, 2003; Perry and Green, 2008).

$$log_{10}Y = -0{,}783 log_{10}X + 1{,}252B \tag{3}$$

where:

$Y = operating\ labour\ (operator\ hours/processing\ step\ per\ short\ tons\ of\ product)$
$X = plant\ capacity\ (short\ tons\ of\ product/day)$
$B = constant\ depending\ on\ the\ type\ of\ process$
$B = 0{,}132\ (for\ batch\ operations\ with\ minimum\ labour\ requirements)$
$B = 0\ (for\ operations\ with\ average\ labor\ requirements)$
$B = -0{,}167\ (for\ a\ well-instrumented\ continuous\ process)$

The third method is, according to Peters and Timmerhaus (1991), much more accurate compared to the second one and would be the preferred method to use when necessary information is available. Ereev and Patel (2012) write that the second and the third method are usually used for preliminary estimates, while the first method may be more accurate for new technologies because it is not based on historical data.

If a plant is to operate continuously all year around, shift-crews are needed to cover each shift of every week. If shift-crews work five 8-hour shifts per week (i.e. 40 hours per week), a minimum of 4,2 shift-crews are needed to cover each shift of the week (Couper, 2003; Garrett, 1989; Perry and Green, 2008). However, it is common among large companies to assume that five shift-crews working 40 hours a week are needed as this will take vacation, holidays and sick days into accounts as well as it gives flexibility in scheduling (Garrett, 1989). When the required operating labour has been estimated, the operating labour expense is calculated by multiplying the number of required employees with the average salary for labour, which can vary significantly among different countries (Ereev and Patel, 2012). In Sweden, the average monthly salary for a machine operator within various processes is 30 100 SEK (Statistics Sweden, 2020a). According to Peters and Timmerhaus (1991), about 15% of OpEx consists of operating labour.

2.6.2.3 Utilities

Electricity, cooling water, compressed air and fuel are examples of utilities that may be required for the operation of a plant (Perry and Green, 2008; Peters and Timmerhaus, 1991; Towler and Sinnott, 2013). Expenses for utilities can generally be estimated in two ways. Couper (2003), Ereev and Patel (2012), Garrett (1989), and Perry and Green (2008) write that the required utilities can be estimated from the material and energy balance of the plant, and thereafter the expense is based on the unit price of respective utility. It is, however, important to review utility prices periodically as they can change over time and thus affect OpEx (Couper, 2003; Humphreys, 2005; Perry and Green, 2008). Peters and Timmerhaus (1991) explain that a rough approximation of utility expenses are 10-20% of OpEx, while Towler and Sinnott (2013) state that utility expenses typically are 5-10% of OpEx.

2.6.2.4 Maintenance

Expenses for maintenance consist of labour and materials, where labour usually makes up about 50% of the expense and material makes up the other 50% of the expense (Couper, 2003; Humphreys, 2005; Perry and Green, 2008; Peters and Timmerhaus, 1991). Maintenance can be considered a semi-variable expense. That is, if the production rate decreases from full capacity to 75 percent, the maintenance expense will decrease to about 85 percent. If the production rate decreases to 50 percent of full capacity, the maintenance expense will decrease to about 75 percent (Humphreys, 2005; Peters and Timmerhaus, 1991), and if the production rate is zero, the maintenance expense is still 30% of the expense at full capacity (Humphreys, 2005). Scholars present several approaches for estimating the maintenance expense. Peters and Timmerhaus (1991) suggest that expense for maintenance amount to approximately 6% of the FCI. Couper (2003), and Perry and Green (2008) suggest that the expense amount to approximately 6-10% of the FCI, Bailie et al. (2018) suggest that the expenses amount to approximately 2-10% of the FCI, Garrett (1989) suggest that the expense amount to 2-10% of CapEx excluding working capital, and Towler and Sinnott (2013) suggest that maintenance expenses amount to 3-5% of the ISBL investment.

2.6.2.5 Supervision

In all plants, supervision is needed to assist with the operation and ensure that the plant is running efficiently (Couper, 2003; Garrett, 1989; Peters and Timmerhaus, 1991). Some scholars bundle supervision together with other labour, such as clerical and engineering (see for example Bailie et al., 2018; Couper, 2003; Garrett, 1989; Peters and Timmerhaus, 1991), while others treat the expense as solely supervision of operating labour (see for example Humphreys, 2005). The expense is nonetheless usually estimated as a percentage of the operating labour expense and ranges from 10 to 30% in literature (Bailie et al., 2018; Couper, 2003; Garrett, 1989; Humphreys, 2005; Perry and Green, 2008; Peters and Timmerhaus, 1991; Towler and Sinnott, 2013).

2.6.2.6 Payroll Burden

Payroll burden includes costs for workers’ insurances, pensions, paid vacations and holidays, social security, fringe benefits, etc. and must be paid for each employee at the plant (Couper, 2003; Garrett, 1989; Humphreys, 2005; Perry and Green, 2008; Towler and Sinnott, 2013). The expense can be estimated as 40-45% (Garrett, 1989), 30-45% (Humphreys, 2005), 30-40% (Couper, 2003; Perry and Green, 2008), or 40-60% (Towler and Sinnott, 2013) of the salary paid to employees. However, the percentage can vary greatly in different countries (Humphreys, 2005). In Sweden, an employee with a monthly salary of 30 000 SEK will have a monthly payroll burden of 14 471 SEK (If, n.d.), or about 48%.

2.6.2.7 Operating Supplies

Operating supplies include the miscellaneous supplies that are needed for the plant to run efficiently, such as lubricants, brooms, mops, instruments, etc. (Couper, 2003; Garrett, 1989; Humphreys, 2005; Peters and Timmerhaus, 1991). Scholars estimate the annual expense in different ways. Couper (2003), and Perry and Green (2008) suggest 5-7% of the operating labour expense, Garrett (1989) suggests 0,5-3% of CapEx, Peters and Timmerhaus (1991) suggest 15% of the maintenance expense, and Humphreys (2005) suggests 6% of the operating labour expense or 0,5-1% of CapEx.

2.6.2.8 Royalties and rentals

Royalties and rentals include expenses for licensing patents for various processes, process conditions, control strategies, algorithms, etc. from patent holders, and the expense is often based on the production capacity of the plant (Towler and Sinnott, 2013). However, it may be difficult to estimate the expense based on the production capacity of the plant since royalties can be set up in many different ways, and alternatively a percentage of sales revenue or a percentage of OpEx can be applied to obtain the expense. The percentage of sales revenue can vary between 1-5% (Humphreys, 2005; Perry and Green, 2008), or 0-5% (Couper, 2003; Garrett, 1989), and the percentage of OpEx can vary between 0-6% (Bailie et al., 2018).

2.6.2.9 Laboratory/quality control

Laboratory expenses include lab supplies and labour required for quality control of products and processes (Couper, 2003; Garrett, 1989; Peters and Timmerhaus, 1991), and for troubleshooting (Bailie et al., 2018). The expense is usually estimated as a percentage of operating labour. Bailie et al. (2018), Garrett (1989), Perry and Green (2008), and Peters and Timmerhaus (1991) suggest using a percentage of 10-20%, Humphreys (2005) suggests 3-10% but writes that it can be as high as 20%, Silla (2003) suggests 20% and Couper (2003) suggests 15-20%.

2.6.2.10 Environmental control

All plants must consider the environmental impact they have and dispose the waste they produce in a safe manner (Couper, 2003; Perry and Green, 2008). As environmental concerns and regulations regarding the environment are increasing, environmental control costs are also increasing (Bailie et al., 2018; Garrett, 1989; Humphreys, 2005). The most reliable way of estimating the expense is to calculate the cost individually for each plant (Humphreys, 2005), which, according to Bailie et al. (2018), can be done by identifying the wastewater streams of the plant in a flow diagram. The cost of wastewater treatment varies between 390 and 532 $\text{SEK}_{\$}$ per 1000 m^3 of wastewater (Bailie et al., 2018).

2.6.2.11 Plant overhead

There is a lack of consensus in literature of what constitutes plant overhead, and consequently, there is no standard way of estimating the expense. In Table 8, different scholars' view on the expense plant overhead is presented.

Table 8. Various scholars’ views on the expense plant overhead.

Included in the expense plant overhead	**Estimation of the expense**	**Source**
Property insurance; personal and property liability insurance; workmen’s compensation; franchise and real estate taxes; fire protection; safety; plant security; maintenance of roads, yards, and docks; plant personnel staff; cafeteria expenses.	3-5% of the FCI.	Couper (2003)
Hospital and medical services; general engineering; safety services; cafeteria and recreation facilities; general plant maintenance and overhead; payroll overhead including employee benefits; control laboratories; packaging; plant protection; janitor and similar services; employment offices; distribution of utilities; shops; lighting; interplant communications and transportation; warehouses; shipping and receiving facilities.	50-70% of the sum of operating labour, supervision and maintenance.	Peters and Timmerhaus (1991)

Administration; indirect labour (laboratory; technical service and engineering; shops and repair facilities; shipping department); purchasing, receiving, and warehousing; personnel and industrial relations; Inspection, safety, and fire protection; automotive and rail switching; accounting, clerical, and stenographic; communications (telephone, mail, and teletype); plant custodial and protective; cafeteria and clubrooms; recreational activities; local contributions and memberships; taxes on property and operating licenses; Insurance (property and liability); nuisance elimination (waste disposal and pollution control)	40-60% of the sum of labour, supervision and maintenance.	Humphreys (2005)
Property taxes; personal and property liability insurance premiums; fire protection; plant safety and security; maintenance of plant roads, yards and docks; plant personnel staff; cafeteria expenses (if one is available).	2-4% of the FCI.	Perry and Green (2008)
Medical and recreational facilities; purchasing; warehousing; engineering; plant protection; maintenance on roads and sewers.	50% of the sum of direct labour, maintenance labour and supervision.	Winter (1969)
Indirect labour; supervision; fringe benefits; medical facilities; fire, safety and security; waste treatment facilities; packaging facilities; restaurant facilities; recreation facilities; salvage services; quality control laboratories; shipping; receiving facilities; storage facilities; maintenance facilities	Fringe benefits are estimated as 22% of the sum of direct labour and supervision. The remaining are estimated as 50% of the sum of direct labour and supervision.	Silla (2003)
Payroll and accounting services; fire protection and safety services; medical services; cafeteria and any recreation facilities; payroll overhead and employee benefits; general engineering; etc.	50-70% of the sum of operating labour, direct supervisory and clerical labour and maintenance.	Bailie et al. (2018)

2.6.2.12 Contingencies

According to Humphreys (2005) and Peters and Timmerhaus (1991), an expense for contingencies should be added to OpEx to account for unforeseen events, such as strikes, storms, and floods. The expense typically amount to 1-5% of OpEx.

2.6.2.13 Property taxes

The expense for property taxes depends on where the plant is located (Winter, 1969). To best evaluate the property tax expense, the authority where the plant is located should be consulted. However, some scholars suggest that the expense can be estimated from the capital investment. Silla (2003) suggests an annual property tax expense corresponding to 2% of the FCI, Winter (1969) suggest 2-3% of the FCI, Peters and Timmerhaus (1991) suggest 1-4% of the FCI and Towler and Sinnott (2013) suggest 1% of ISBL plus OSBL capital cost. In Sweden, the property tax for industries and CHP plants is 0,5% of the assessed property value (The Swedish Tax Agency, n.d.). The assessed value of a property corresponds to 75% of the probable market value for properties in the area (The Swedish Tax Agency, n.d.).

2.6.2.14 Insurance

Plants are generally required to have insurance for property and personal liability (Garrett, 1989). The expense varies depending on the type of processes and hazards present in the plant (Garrett, 1989; Peters and Timmerhaus, 1991; Winter, 1969). It is typically estimated as a percentage of a part of the capital investment. Peters and Timmerhaus (1991), Silla (2003), and Winter (1969) suggest an estimate of about 1% of the FCI while Towler and Sinnott (2013) suggest 1% of ISBL plus OSBL. Bailie et al. (2018) combine insurance with local property taxes and suggest that these two expenses amount to approximately 1,4-5% of the FCI. Garrett (1989) combines insurance with various local taxes, fees, miscellaneous licenses and permits and suggests that these expenses amount to approximately 3-5% of the total plant cost.

2.6.2.15 Rent

An expense for rent can incur if buildings or land are leased. It can be preferable to rent buildings and/or land instead of purchasing as the latter means that capital has to be tied up in the land and/or buildings (Towler and Sinnott, 2013). If land or buildings are rented, rent corresponding to 8-12% of the land or buildings' value should be included in OpEx (Peters and Timmerhaus, 1991).

2.6.2.16 R&D

Research & development is necessary to improve processes and products in the plant (Silla, 2003). The expense for R&D can be estimated either as a percentage of sales revenue or as a percentage of OpEx. Garrett (1989), Peters and Timmerhaus (1991) and Silla (2003) estimate the expense based on sales revenue, with a percentage of 0,5-5%, 2-5%, and 3,6-8%, respectively. Winter (1969) suggests using 2-4% of sales revenue or 3,5-8% of OpEx and Bailie et al. (2018) suggest that the expense is estimated as 5% of OpEx.

2.6.2.17 Sales & marketing and Distribution & packaging

The product produced in a plant must, in some way, be sold and delivered to customers, and the expense for this is denominated as sales & marketing and packaging & distributing. As with the expenses in plant overhead, there are many different views on what is included and how to estimate this expense. Couper (2003) writes that the expense for packaging, loading, and shipping the product can be estimated as 0-7% of the sales revenue. The expense for both sales and distribution is, according to Garrett (1989), estimated as 2-10% of the sales revenue. Peters and Timmerhaus (1991) write that expenses for sales & marketing, such as “salaries, wages, supplies, and other expenses for sales offices; salaries, commissions, and traveling expenses for salesmen; [...] advertising expenses; and technical sales service” (p.207), and distribution & packaging amount to approximately 2-20% of OpEx. Silla (2003) writes that expenses for sales & marketing and distribution & packaging amount to 5-22% of OpEx, with an average value of 13,5. Both Silla (2003) and Peters and Timmerhaus (1991) write that products sold in small quantities to many different customers have more significant expenses, while bulk products sold to fewer customers have fewer expenses. Towler and Sinnott (2013) treat sales &

marketing, which includes “costs of paying the sales force, advertising costs including promotional materials, travel to visit customers and trade shows, and other costs associated with closing sales” (p.379) and “costs of market research and analysis, competitive studies, branding, and any other costs associated with developing an understanding of customer needs and preferences” (p.379), separately from distribution & packaging. They suggest that the expense for sales & marketing amount to 0-5% of OpEx, where bulk products have a lower figure and more specialised products have a higher figure. Bailie et al. (2018) state that the costs for selling and distribution of chemical products are estimated as 2-20% of OpEx.

2.6.2.18 Administrative

Estimation methods and costs included in the administrative expense vary in literature and among scholars. Garrett (1989) estimates that administrative costs amount to 2-10% of sales revenue. Peters and Timmerhaus (1991) include “salaries and wages for administrators, secretaries, accountants, stenographers, typists, and similar workers" (p.206) as well as “costs for office supplies and equipment, outside communications, administrative buildings, and other overhead items related with administrative activities" (p.206) in the administrative expense and suggest that it is estimated as 20-30% of operating labour. Winter (1969) includes “management salaries, legal fees, and auditing charges incurred in the over-all management of all phases of the company’s enterprise” (p.50) in the administrative expense and suggest that the expense is estimated either as 2-3% of sales revenue or as 3-6% of OpEx. Towler and Sinnott (2013) include “general management, human resources, purchasing and procurement, finance, accounting, strategic planning, business development, property management, information technology, health, safety and environment, corporate communications, and legal services" (p.379) in administrative costs. They suggest that the expense is estimated as 65% of labour salary and payroll overhead plus supervision salary and payroll overhead. Silla (2003) includes costs for executive, clerical, engineering, legal, and communications in the administrative expense and suggests that an estimation of this expense is 3-6% of OpEx. Bailie et al. (2018) suggest that administrative costs can be estimated as 15% of operating labour plus direct supervisory and clerical labour plus maintenance.

2.6.3 Non-operational expenses

The non-operational expenses of depreciation, interest, and income taxes are not directly related to the operation of a plant but must nevertheless be considered before the economic feasibility of a plant can be analysed.

2.6.3.1 Depreciation

Depreciation is not an actual expense in terms of cash flow but rather a concept where the initial cost of constructing a plant (i.e. the CapEx) is distributed over its expected lifetime to reflect the wear and cost of the plant more accurately (Garrett, 1989). Depreciation can be considered a noncash charge that is reported as an expense, consequently reducing income for taxation purposes (Towler and Sinnott, 2013). Several depreciation methods can be used, such as straight line, declining balance, sum-of-the-years digits, double-declining balance, units of projection, accelerated cost recovery system, and modified accelerated cost recovery system (Humphreys, 2005). These methods offer different procedures for allocating the depreciation over the years, but its total value remains the same. Choosing the most appropriate depreciation method depends on several factors related to different accounting practices. However, a straight-line depreciation method should be used when performing preliminary cost estimates for a plant (Couper, 2003; Garrett, 1989; Perry and Green, 2008; Peters and Timmerhaus, 1991; Winter, 1969). An important aspect to remember considering depreciation is that not all parts of the CapEx can be depreciated, such as the cost for land (Towler and Sinnott, 2013). For an asset to be depreciable, it needs to be used in business or held to produce income. It also needs to be useful for at least one year, and be able to wear out, decay, get used up, become obsolete, and lose value due to natural causes (Couper, 2003). The period over which a property is depreciated starts when the investment is placed in business and ready for production of income, and ends either when its cost is fully recovered or when it is retired from service (Perry and Green, 2008).

The straight-line method assumes that the value of the property declines linearly with time and that equal amounts are charged yearly throughout its service life (Peters and Timmerhaus, 1991). The straight-line method is shown in equation 4 (Couper, 2003; Garrett, 1989; Peters and Timmerhaus, 1991).

$$d = \frac{(V - S)}{n} \tag{4}$$

where:
$d = annual\ depreciation$
$V = original\ value\ of\ the\ asset$
$S = salvage\ value$
$n = expected\ service\ life$

The salvage value is usually set to zero because the cost for dismantling and selling the equipment is often nearly equal to the revenue that would be received (Garrett, 1989). Furthermore, Westney (1997) writes that the salvage value should be assumed to be zero when performing economic analyses.

2.6.3.2 Interest

Interest, “the compensation paid for the use of borrowed capital” (Peters and Timmerhaus, 1991, p.207), is directly dependent on the amount of capital borrowed for the capital investment. Therefore, it must be treated individually for each plant depending on how much capital is borrowed to finance the plant (Garrett, 1989). The interest on borrowed capital could be considered an operating cost, but Peters and Timmerhaus (1991) argue that it is preferable to separate it from other fixed charges and instead list it as a financing cost or as general heading of management. The size of the interest expense is dependent on the interest rate and the size of the loan. The interest is influenced by factors such as bond markets, government central bank, scarcity of money, loan size, length of the loan period, the creditworthiness of the borrower, and the present economic conditions (Perry and Green, 2008; Towler and Sinnott, 2013). Typical interest rates of borrowed capital for manufacturing plants are 2-6% (Winter, 1969) or 5-10% (Peters and Timmerhaus, 1991).

2.6.3.3 Income taxes

In most countries, companies and corporations must pay income tax. The income tax is calculated by multiplying a company's annual net profit with the income tax rate (Peters and Timmerhaus, 1991). The net profit is defined as total revenues minus total expenses, including depreciation and net interest expenses. The corporate tax on yearly profits for Swedish companies is 20,6% from 2021 and onwards (Skatteverket, n.d.). At the time of writing, there are no local income or municipal taxes applied to Swedish corporations (Skatteverket, n.d.).

2.6.4 Plant financing

A large amount of capital is needed for financing an investment in a plant. The way this capital is raised influences factors such as cost of capital and interest costs, which, in turn, have a profound impact on the profitability of an investment. The funding available can be divided into internal and external sources (Couper, 2003). Usually, the corporation considering an investment in a plant does not have sufficient internal capital to cover the investment and capital must be raised externally. Debt financing and equity financing are two standard approaches to raising external capital. Few companies depend entirely on equity or debt financing alone but use a combination of both (Towler and Sinnott, 2013). The debt-equity ratio for companies within the green and renewable energy sector in USA has been estimated to be 52.97% debt and 47.03% equity (Damodaran, 2020). Debt capital is primarily raised by the issuing of long-term bonds, while equity capital is contributed by stockholders, combined with the internal earnings used for reinvestment in the business (Towler and Sinnott, 2013). When issuing a debt loan, apart from the interest paid to borrow capital, the loan itself must also be paid back to the lender. This can either be done by amortising over the loan period or by paying back the loan as a lump sum at the end of the loan period. The most suitable funding option depends on factors such as the state of the economy, inflation, the company's current debt, and the cost of capital (Perry and Green, 2008).

The cost of capital is the cost for a company to use capital issued by debt and equity (Perry and Green, 2008). Consequently, to make a profit, an investment needs to have a higher return than the cost of capital. The weighted average cost of capital (WACC), also called overall cost of capital, is often used as the cost of capital and is derived from the capital structure of a company (Pratt and Grabowski, 2014). With the help of the WACC, future cash flows can be discounted to a present value and thus enabling the valuation of investments. Value can be said to be created when an investment provides a higher return than the WACC, and, vice versa, value is destroyed when an investment provides a return smaller than the investment (Karlson, 2015). The average WACC for companies within renewable energy in Europe was approximately 6,5% in 2016.

(Deloitte, 2017). In 2019 the Swedish energy companies Vattenfall and Stockholm Exergi used an after-tax WACC of 4,5–6,9% for non-captive markets (Vattenfall, 2019) and 7.6% (Stockholm Exergi, 2019), respectively.

2.7 Theoretical framework

To obtain a different view on the feasibility of developing a combined pyrolysis and CHP plant for CDR purposes and its potential for mitigating climate change, a sociotechnical perspective regarding technological change in the CHP sector can be applied. Although the economic feasibility is an essential aspect of the development of a new technology or innovation, a sociotechnical perspective can provide additional insights regarding the development of new technologies and innovations (Cherp et al., 2018), such as a combined pyrolysis and CHP plant.

One way of understanding the dynamics of technological change is by using the Multi-Level Perspective (MLP). The MLP is a conceptual model consisting of three levels which can be used "to understand the complex dynamics of sociotechnical change" (Geels, 2002, p.1259). Each level contains a heterogeneous configuration of elements and higher levels are more stable regarding the number of actors, and the degrees of alignment between the elements (Geels, 2011). Technological transitions occur through the alignment of processes between and within the three levels (Geels et al., 2017).

The macro-level in the MLP, called the sociotechnical landscape, can be described as the broader context which influences the dynamics of the lower levels (Rip and Kemp, 1998). Contrastingly, the lower levels only have limited influence on the landscape level in the short run (Geels, 2011). The metaphor landscape relates to the exogenous environment and its relative hardness (Geels, 2004). The landscape includes a set of diverse elements deeply rooted in society, such as societal values, demographic trends, political ideologies, macro-economic trends (Geels, 2011), electricity infrastructure, and climate change (Geels 2002). These elements constitute material environments, symbols, and values that are hard to deviate from, forming "gradients" for action (Geels, 2004). Generally, these types of elements are robust, and their development is slow-moving. However, the landscape can be exposed to exogenous shocks such as wars, political upheavals, economic crisis, and major accidents, which facilitate breakthroughs of radical innovations due to the destabilisation of the system (Geels et al., 2017). An example of the latter is the Fukushima accident in 2011, which triggered Germany to face out its nuclear power and set energy transition on the political agenda (Geels et al., 2017).

The meso level in the MLP, called the sociotechnical regime, accounts for the stability of sociotechnical systems, and it can metaphorically be compared to a "deep structure" (Geels, 2004). The regime consists of a set of rules "embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways of handling relevant artifacts and persons, ways of defining problems - all of them embedded in institutions and infrastructures" (Rip and Kemp, 1998, p.338). Regimes are characterised by lock-in and incremental innovation that occur in small adjustments into stable trajectories (Geels, 2004). Existing trajectories are stabilised by cognitive routines, regulations and standards, lifestyle adoption to technical systems, and sunk investments (Geels and Schot, 2007). The trajectories are not limited to technology but also include cultural, political, scientific, market, and industrial dimensions (Geels and Schot, 2007). All these dimensions have dynamics that are coordinated by sub-regimes, but they also co-evolve and interpenetrate each other (Geels and Schot, 2007).

The micro level in the MLP, called the niche-level, is somewhat protected from the set of rules in the regime level and acts as an incubation room for radically new innovations and technologies (Schot, 1998). Initially, niches suffer from low performance due to unstable sociotechnical configurations (Geels and Schot, 2007), and there might be a mismatch with the existing regime dimensions such as regulations, consumer practises or absence of fitting infrastructure. However, if niches manage to develop properly, they can reach the regime level. Examples of niches are subsidised demonstration projects, R&D laboratories, and small market niches with particular user demand and a willingness to support emerging innovations (Geels, 2011). Niche-innovations are often developed by small networks of fringe actors (Geels and Schot, 2007) under the surface of incumbent regime actors (Geels, 2010). According to niche-innovation literature, there are three core processes for niche development (Kemp et al., 1998; Schot and Geels, 2008):

1) The articulation of expectations or visions, which aim is to increase attention and engage external actors in funding.
2) Enrolment of more actors and building of social networks which broaden the base of resources for the niche-innovation.
3) Learning and processes of articulation on several dimensions such as technical design, business models, and infrastructure requirements.

Momentum for a niche innovation is gained when expectations become more definite and widely accepted, and when networks become larger. Usually, incumbent actors defend, maintain, and incrementally improve the existing sociotechnical systems (Geels, 2017), impeding new niche actors to establish. Nevertheless, if large, powerful actors support a niche innovation, its legitimacy is further conveyed (Geels, 2011). Furthermore, if development on the landscape level puts pressure on the regime so that tensions, cracks, and windows of opportunities arise, a niche innovation can break through more extensively (Geels, 2010).

Although distinct from each other, the three levels in the MLP are interconnected as “regimes are embedded within landscapes and niches within regimes” (Geels, 2002, p.1261). A key point in the MLP is that transitions emerge “through the interplay of processes between the processes at different levels (Geels, 2005). A technological transition occurs through the dynamics of the three levels. Niche-innovations build up momentum through performance improvements and support from powerful groups. Pressure is put on the regime due to changes at the landscape level, and destabilisation of the existing regime creates an opportunity for a niche-innovation to emerge (Geels and Schot, 2007). When a niche innovation breaks through to the mainstream markets, it starts competing with the existing regime.

3 Methodology

In this chapter, the research design (chapter 3.1), research process (chapter 3.2), data collection (chapter 3.3), and research quality (chapter 3.4) of the thesis are firstly presented. Thereafter, to answer SRQ1 and SRQ2 of this thesis, a quantitative analysis of the costs (chapter 3.5) and benefits (chapter 3.6) of an investment in the plant has been performed. The costs include CapEx, OpEx, and non-operational expenses. The benefits include sales of electricity, sales of electricity certificates, sales of biochar, cost savings incurred from heat production, and funding from Klimatklivet for producing biochar. Furthermore, a cash flow analysis (chapter 3.7) throughout the investment time horizon has been performed from which the NPV of an investment in the plant is obtained and used to evaluate the economic feasibility of the plant. To answer the MRQ of this thesis, a sensitivity analysis (chapter 3.8) has been made to evaluate which parameters have greatest impact on the economic feasibility of the plant. Lastly, to answer SRQ3 of this thesis, the results are discussed in relation to the dynamics of technological change in the CHP sector using the MLP (chapter 5.3).

The economic lifetime of the plant is assumed to be 20 years and the investment time horizon is set to 23 years, which includes two years of construction and one year for decommissioning the plant. It is assumed that the land needed for the plant is bought and not rented. All calculations have been made in Microsoft Excel.

3.1 Research design

This thesis has been conducted as a quantitative study. The reasoning behind this choice is that quantitative studies provide a good overview of phenomenon (Blomkvist and Hallin, 2015), which, in this study, is the relatively unexplored combined pyrolysis and CHP plant. Additionally, through quantitative studies, the measurement of the strength of variables and their influence on a phenomenon can be seen (Blomkvist and Hallin, 2015), which is in line with the MRQ of this thesis. Due to the combined pyrolysis and CHP plant being a novel and unexplored area, an exploratory research approach was chosen. At the start of the project, it was clear that the focus would be on the feasibility of a combined pyrolysis and CHP plant, but in what aspects remained subject to change during the work process. An exploratory approach was deemed appropriate since it enables flexibility and change of research direction as new data and insights appear (Saunders et al., 2016). Furthermore, an exploratory study might show that the research is not worth pursuing (Saunders et al., 2016), which, in the case of this study, would mean that it is not feasible to construct a combined pyrolysis and CHP plant for CDR purposes. An exploratory research approach is often combined with an inductive approach since it is unknown what exactly one is looking for (Blomkvist and Hallin, 2015). An inductive approach is used when conducting an empirical study on an identified problem and using theory to develop a better understanding of the findings (Blomkvist and Hallin, 2015). As this is the case of this study, an inductive approach was combined with an exploratory approach.

3.2 Research process

The first phase of the research process was of exploratory and unstructured nature. The empirical context of the subject was investigated and informal talks were held with employees at the Heat and Power Division at AFRY to obtain a deeper understanding of the problem of constructing a combined pyrolysis and CHP plant. In this phase, the authors mainly gathered relevant background information, which is presented in chapter 2. The mass and energy balance model of a combined pyrolysis and CHP plant was developed by a Senior Process Engineer at AFRY. The authors mediated a general idea of the model, mainly in terms of capacity and input & output variables. After the model was developed, literature regarding plant economics were reviewed and data were collected in parallel with economic calculations, allowing the authors to distinguish important variables affecting the economic feasibility. The economic calculations were then analysed and discussed in relation to pertinent literature and the theoretical framework. Lastly, conclusions from the analysis and discussion were deduced. Constructive feedback on the work was continuously received throughout the work process, from the authors' supervisor and examiner at KTH and contact person at AFRY. Feedback was also received at three seminars with other master students at the School of Industrial Engineering and Management at KTH.

3.3 Data collection

Data has mainly been collected through a document gathering strategy. This means that there was a need to be careful with the information since it was originally gathered for other research purposes (Saunders et al., 2016). Secondary data is initially collected for other research purposes and includes raw data and published summaries (Saunders et al., 2016). Benefits of using secondary data is that it can be further analysed to provide additional or distinct knowledge, interpretations, and conclusions (Bulmer et al., 2009). Additionally, one of the main advantages of using secondary data is the enormous saving in time (Vartanian, 2011). Initially, the authors intended to collect primary data. However, in consultation with the authors' contact person at AFRY, it was concluded that the collection of reliable primary data would take up most of the resources available for this thesis and thus not contribute as much to evaluating the economic feasibility of the combined pyrolysis and CHP plant. It was therefore decided that it would be more beneficial to use secondary data and focus more of the resources on economic modelling of the plant. The collected data were mainly obtained through research databases provided by KTH. Other sources include organisations' websites and annual reports of companies. For chapter 2.6, information was primarily gathered from handbooks for engineering and chemical engineering plants.

3.4 Research quality

The measures taken for ensuring a reduced bias and a high quality of the thesis are related to the concepts of reliability, replicability, and validity. Reliability refers to the degree of replication (Saunders et al., 2016) and the consistency of a measure (Heale and Twycross, 2015). In this thesis, high reliability has been achieved by describing each assumption and calculation as precisely as possible, referring to the background chapter for sources when necessary. This procedure allows others to reproduce the calculations and obtain the same results, thus creating replicability. Validity is the appropriateness of the used measures and the accuracy of the analysis of the results (Saunders et al., 2016). A higher validity has been aimed at by using multiple sources for cost data and estimations when possible. However, due to the research area of this thesis being relatively unexplored, comparisons of results with data from real plants and from different sources, which increase validity (Spek et al., 2017), have been difficult to perform.

3.5 Costs

In this chapter, the costs of the plant are evaluated. The costs include CapEx, OpEx, and the non-operational expenses of depreciation, interest and taxes.

3.5.1 CapEx

The CapEx of an investment in the combined pyrolysis and CHP plant consists of FCI, start-up expenses, land cost and working capital, as shown in equation 5.

$$CapEx = FCI + Startup\ expenses + Land + Working\ Capital \tag{5}$$

$The\ Fixed\ Capital\ Investment$ consists of all expenses related to preparing the plant for operation. It includes purchase, delivery and installation of all process equipment as well as the cost for other physical features such as buildings and roads. Engineering charges for planning, design and projection and construction costs for labour and material are also part of the FCI. Furthermore, contingency charges are included in the FCI, which covers unforeseen costs like changes of prices and project scope. In literature (see chapter 2.6.1.1) it is suggested that the FCI should be estimated based on the cost of the major process equipment in the plant. However, with the resources available for this thesis, no reliable data, such as proprietary data from a suitable vendor, regarding the cost of major process equipment of the combined pyrolysis and CHP plant, especially regarding the RHF, could be obtained. Therefore, instead of estimating the FCI based on unreliable equipment cost data, a reversed approach is used where the maximum value of the FCI is calculated, with the premise that an investment in the plant should have an NPV of zero. This will give an indication of how much the FCI of the combined pyrolysis and CHP plant is allowed to be if an investment in the plant is to be economically attractive to an investor and will thus provide details about the economic feasibility of the plant. The FCI is calculated by finding the value of the FCI which generates an NPV of an investment in the plant equal to zero. This is done using the goal seek function in Microsoft Excel where the target value of the NPV is zero and the FCI is set as a changeable variable. The calculation of the NPV is reviewed in chapter 3.7.

$Startup\ expenses$ incur during the first year of plant operation and are needed for preparing the plant to function properly. It includes costs for employee training, testing and adjustment of equipment. Due to the novelty and relative uncertainty of the pyrolysis technology, the start-up expenses are estimated as 12% of the FCI, which is the upper spectra of what Baasel (1976) and Peters and Timmerhaus (1991) suggest.

$Land$ is calculated as 3% of the FCI, in accordance to what is suggested by Couper (2003). This is considered reasonable since the plant most likely would be located in the outskirts of a city, in a less densely populated region where land costs are lower compared to central areas.

$Working\ Capital$ is the capital which is tied up in raw material, inventories, products, accounts receivable and accounts payable. The working capital is estimated to constitute 15% of the CapEx, which is the average percentage suggested by Winter (1969), Humphreys (2005) and Towler and Sinnott (2013). The working capital is obtained by first calculating the sum of the fixed capital investment, start-up-expenses and land and then dividing the sum by 0.85 to obtain the total CapEx. Afterwards, the fixed capital investment, start-up-expenses and land are subtracted from the total CapEx to obtain working capital.

3.5.2 OpEx

To obtain the OpEx, all expenses incurred during operation of the plant are summed, as shown in equation 6. The annual operating time of the plant is 8000 hours and all expenses are therefore estimated on an annual basis with an on-stream time factor of 8000 hours.

$$OpEx = C_{RM} + C_{OL} + C_{PO} + C_{S\&D} + C_U + C_E + C_A + C_C + C_{R\&R} + C_M + C_{CHP-O\&M} + C_{S\&C} + C_{PB} + C_{OS} + C_{QC} + C_{PT} + C_I + C_{R\&D} \tag{6}$$

C_{RM} is the cost for raw material, i.e. grot, needed for producing biochar and to generate heat and electricity in the plant. The amount of raw material needed per year is calculated by multiplying the grot input in the plant (20 000 kg wet biomass/hour) with the annual operating hours of the plant (8000 hours/year). This amount can be expressed in terms of energy input when multiplied with the heating value of grot (10,7 MJ/kg). Thereafter, the cost can be calculated by multiplying the energy input with a conversion factor between MJ and MWh (1/3600 MWh/MJ) and the price of grot (199 SEK/MWh). The price of grot is based on the average price that heating plants in Sweden in 2019 paid for forest chips including transport to the plant (The Swedish Energy Agency, 2020). Forest chips are defined as grot and other wood from clearing of coniferous and deciduous forest (The Swedish Energy Agency, 2018).

C_{OL} is the cost for operating labour and can be estimated by using one of the three methods presented in chapter 2.6.2.2. The method developed by Wessel requires knowledge about the number of processing steps in the plant which cannot be obtained directly from the model of the plant and is therefore not used. The method developed by Ulrich (1984) can also not be used as some equipment in the plant is not covered in the list presented by Ulrich (1984). Therefore, using the method presented by Peters and Timmerhaus (1991), a value of four operating hours per tonne product is applied to obtain the number of operators needed in the plant. A value of four is chosen as values between four and eight are appropriate for plants producing a solid product, such as biochar. It is assumed that the plant would be in the lower part of this range as the plant will be large scale with highly automated and continuous operations. The number of operators needed to run the plant for one shift is calculated by multiplying the value of four with the amount of biochar produced in the plant (2,5 tonne/hour) and round it up to the closest integer as a fraction of an employee cannot be hired. The total number of operators employed at the plant is then calculated by multiplying the number of operators needed to run the plant for one shift (10 operators) with the number of shift crews needed to cover all the shifts in the plant. The number of shift crews needed is assumed to be five to account for vacation, holidays and sick days, as suggested by Garrett (1989). The cost for operating labour is then calculated by multiplying the total number of operators employed at the plant (50 operators) with the annual salary of an operator in Sweden. The monthly salary of an operator in Sweden is assumed to be 30 100 SEK (Statistics Sweden, 2020a), which means that the annual salary for an operator is 361 200 SEK.

C_{PO} is the cost for plant overhead and include expenses such as fire protection; plant safety, security and inspection; health/medical services; general engineering/technical service; general plant maintenance and repair; cafeteria, restaurant and recreational facilities; janitorial services and similar; lightning; receiving facilities; transportation and communication and salvage services. The reason for not including, for example, R&D, payroll burden, insurance or laboratory/quality control in plant overhead, which is not uncommon in literature, is because these expenses instead are treated as individual expenses. This minimises the risk of accidentally omitting an expense, which is the largest source of error when estimating OpEx (Winter, 1969). Plant overhead is estimated by multiplying the sum of operating labour, supervision and maintenance with 0,25. This is significantly lower than what is suggested in literature (see for example Peters and Timmerhaus (1991) who suggest using a multiplier between 0,5 and 0,7). However, a multiplier of 0,25 is seen as reasonable as scholars, such as Peters and Timmerhaus (1991), include sizeable costs such as payroll burden, control laboratories and packaging facilities in plant overhead, which, as seen above, is not included in this estimation.

$C_{S\&D}$ is the cost for sales & marketing and distribution & packaging. The expenses included in sales and marketing are salaries and traveling expenses of sales force, supplies for sales offices and advertising/marketing and promotional activities. Included in distribution & packaging are expenses for packaging, warehousing and shipping. The cost for sales & marketing and distribution & packaging is estimated by multiplying the sales revenue of biochar, $R_{Biochar}$, with 0,03. A multiplier of 0,03 of the sales revenue is somewhat lower than the average multiplier suggested by Couper (2003) and Garrett (1989) but is deemed reasonable as biochar can be seen as a bulk commodity, which, according to Silla (2003), Peters and Timmerhaus (1991) and Towler and Sinnott (2013), have less expenses for sales & marketing and distribution & packaging.

$C_U$is the cost for utilities, which are needed during operation of the plant. Although this cost can be estimated as a percentage of the OpEx, it is in this thesis estimated from the mass and energy balance of the plant as it will give a more accurate reflection of the actual need for utilities. The only utility present in the plant is electricity, which is needed for mechanical dewatering of biomass, and corresponds to 325 kW. To obtain the cost for this utility, the electrical power of 325 kW is multiplied with the annual operating hours of the plant (8000 hours/year) and the price of electricity (0,66 SEK/kWh). The price of electricity is based on the average price for electricity for industries in Sweden with an annual consumption between 2000 and 20 000 MW between the period January-June 2019 (Statistics Sweden, 2020b).

C_E is the cost for environmental control and includes the cost for handling wastewater (Bailie et al., 2018). From Figure 2, it is known that the wastewater from the plant is 33,83 kg/s. With an annual operating time of 8000 hours, the annual amount of wastewater from the plant is calculated to be 974 304 000 kg. The cost for environmental control is then calculated by multiplying the annual amount of wastewater from the plant with the average cost for treating wastewater (0,461 SEK/m^3, as suggested by Bailie et al., 2018), and with a conversion factor between kg and m^3 for water (1/1000 kg/ m^3).

C_A is the cost for administrative work in the plant and includes expenses for executives, management, administrators, secretaries, HR, purchasing, financing/accountants, legal, IT, office supplies and equipment (including IT and communications) as well as administrative facilities. The cost for administrative is estimated by multiplying the cost of operating labour, C_{OL}, with 0,25, which is the average multiplier suggested by Peters and Timmerhaus (1991).

$C_C$is the cost for contingencies and is assumed to be 3% of OpEx, which is the average of what is suggested by Humphreys (2005) and Peters and Timmerhaus (1991). To calculate the expense, all operational expenditures except contingencies are summed and divided by 97%, which gives the total OpEx. Thereafter, to obtain the cost for contingencies, all operational expenditures except contingencies are subtracted from the total OpEx.

$C_{R\&R}$ is the cost for royalties and rentals. As this expense is more concerned with the production of biochar than the generation of electricity and heat, it is solely based on the sales revenue of biochar. The expense is obtained by multiplying the sales revenue of biochar, $R_{Biochar}$, with 0,0275, which is the average of what is suggested by Humphreys (2005), Perry and Green (2008), Couper (2003) and Garrett (1989).

$C_M$is the cost for maintenance of the plant and is calculated as the sum of maintenance labour, C_{ML}, and maintenance material, C_{MM}. Both maintenance labour and maintenance material is calculated by multiplying the FCI with 0,03, as suggested by Bailie et al. (2018) and Peters and Timmerhaus (1991).

$C_{CHP-O\&M}$ is the cost for O&M for the CHP part of the plant. The cost is calculated by multiplying the specific O&M cost for CHP plants in Sweden (200 SEK/MWh) (Colnerud Granström, 2011) with the annual amount of heat and electricity produced in the plant. The annual amount of heat and electricity produced in the plant is calculated by respectively multiplying the electrical (5,3 MW) and heat (14,4 MW) output of the plant with the annual operating hours of the plant (8000 hours/year).

In Table 9, the remaining variables in equation 6 are displayed together with the method for estimating each cost. The estimation of each expense is based on suggestions from literature, which can be found in chapter 2.6.2.

Table 9. Remaining variables in equation 6 with respective methods for estimation of expenses.

Variable	Expense	Estimation of expense
$C_{S\&C}$	Supervision and clerical labour	$C_{S\&C} = 0{,}2 * C_{OL}$
C_{PB}	Payroll burden	$C_{PB} = 0{,}48 * (C_{OL} + C_{ML} + C_{S\&C})$
C_{OS}	Operating supplies	$C_{OS} = 0{,}06 * C_{OL}$
C_{QC}	Laboratory/quality control	$C_{QC} = 0{,}15 * C_{OL}$
C_{PT}	Property taxes	$C_{PT} = 0{,}02 * FCI$
C_{I}	Insurance	$C_{I} = 0{,}01 * FCI$
$C_{R\&D}$	R&D	$C_{R\&D} = 0{,}045 * R_{Biochar}$

3.5.3 Non-operational expenses

The non-operational expenses consist of depreciation, interest and taxes, as shown in equation 7, and are calculated on an annual basis.

$$Non\ operational\ expenses = C_D + C_{INT} + C_T \qquad (7)$$

C_D, is the annual depreciation which is applied to 50% of the FCI. Land, working capital and start-up expenses are not depreciable and are therefore not included in the depreciation expense. Furthermore, as not all parts of FCI are depreciable, such as engineering and supervision, contractor's fee and contingency, it is assumed that 50% of the FCI is depreciable. The annual depreciation is calculated using a linear depreciation method over the economic lifetime of the plant, which is assumed to be 20 years.

C_{INT} is the interest expense for borrowed capital. It is assumed that the debt-equity financing ratio of an investment in the plant is 50-50. This means that half of the capital needed for the CapEx is borrowed as a debt loan. The interest rate of the loan is set to 5% and interest is paid in equal amounts annually during the economic lifetime of the plant. The debt is repaid as a lump sum at the end of the economic lifetime of the plant.

C_T is the cost for taxes. The tax rate is set to 20,6% and is applied to the taxable income. The taxable income is defined as the Earnings Before Tax (EBT), which is calculated by subtracting

OpEx, depreciation and interest from total revenues.

3.6 Benefits

The benefits of the plant include revenue from sales of biochar, electricity and electricity certificates, savings of not having to produce district heating elsewhere and funding from Klimatklivet for producing biochar, as shown in equation 8. All benefits except the funding from Klimatklivet are calculated on an annual basis.

$$Benefits = R_{biochar} + R_{electricity} + R_{electricity\ certificates} + S_{heat} + F_{klimatklivet} \quad (8)$$

The revenue from sales of biochar, $R_{biochar}$, is obtained by multiplying the sales price of biochar with the annual amount of biochar produced in the plant. The annual amount of biochar is obtained by multiplying the biochar output (2,5 tonne/hour) with the annual operating hours of the plant (8000 hours). The sales price of biochar varies greatly in literature, from as low as 675 SEK/tonne to as high as 84 075 SEK/tonne, as seen in Table 2. However, as this study has a Swedish context, the willingness to pay for biochar among soil manufacturers in Sweden, which is between 2600 and 3000 SEK/m3 (Avfall Sverige, 2018), has been used as a basis for the sales price of biochar. To calculate the sales price of biochar in terms of SEK/tonne, the average willingness to pay among soil manufacturers in Sweden (i.e. 2800 SEK/m3) is divided by the density of the produced biochar and multiplied with 1000 to account for the conversion between kg and tonne. The density of the produced biochar is calculated using equation 1 with a wood bulk density of grot corresponding to 275 kg/m3, which is the average bulk density of grot, presented by Strömberg and Herstad Svärd (2012) in Table 1.

The revenue from sales of electricity, $R_{electricity}$, and electricity certificates, $R_{electricity\ certificates}$, is calculated by multiplying the respective sales price of electricity and the sales price of electricity certificates with the annual amount of electricity generated in the plant. The annual amount of electricity produced in the plant is calculated by multiplying the electrical power output (5,3 MW) with the annual operating hours of the plant (8000 hours). An electricity sales price of 401,04 SEK/MWh (Nord Pool, 2019) is used and a sales price of 20 SEK/MWh (Holmström, 2020) is used for electricity certificates .

Heat produced in the plant is assumed to be sold via an energy company's district heating network to its connected customers. The average revenue per amount of sold district heating is assumed to be 653 SEK/MWh, based on the total amount of sold heating and total revenue for sold heating in Sweden in 2018 (Swedish Energy Markets Inspectorate, 2019a). To obtain the revenue from heat production, the specific revenue for heat of 653 SEK/MWh is multiplied with the district heating output of the plant (14,4 MW) and the annual operating hours of the plant (8000 hours). However, it is not plausible to assume that an energy company will have an additional capacity and demand for heat in their DH network. Instead, the produced heat in the plant can replace heating from other heating plants and reduce costs for heat production in the DH network. Thus, the heat produced in the plant is seen as a source for cost savings rather than as a source for revenue. The cost saving is calculated based on the average cost for producing district heating in Sweden in 2018, which is 438 SEK/MWh (Swedish Energy Markets Inspectorate, 2019b). The cost savings from the heat production, S_{heat}, is thus obtained by multiplying the specific cost saving of 438 SEK/MWh with the district heating output of the plant (14,4 MW) and the annual operating hours of the plant (8000 hours).

As the fund Klimatklivet has granted economic support to multiple biochar production plants and it is suggested that this funding should continue, it is assumed that Klimatklivet will provide economic support to help finance the plant. The amount of funding is based on the CO_2e emissions decrease incurred from the plant. From the model of the plant it is known that the carbon content of biochar produced in the plant is 90,9%. The annual amount of carbon contained in the biochar is obtained by multiplying the carbon content with the annual biochar production in the plant (about 20 000 000 kg). However, it is assumed that only 13% of the carbon contained in the biochar can be considered as sequestered and thus accounted for as an emission decrease. This quite conservative percentage is in line with a study by Bach et al. (2016) and is applied to avoid exaggeration of the carbon sequestration potential of the biochar as different types of biochar have different carbon sequestration potentials. In terms of CO_2e, the emission decrease is equal to about 8 600 000 kg CO_2e/year, considering that combusting 1 kg of carbon results in emissions of 3,67 kg CO_2. When applying for funding from Klimatklivet, the timeframe used to calculate the total emission decrease is 30 years for energy conversion technologies such as heat production (Naturvårdsverket, 2019). The total CO_2e emission decrease from the plant is thus calculated by multiplying the annual CO_2e emission decrease of about 8 600 000 kg CO_2e with a time period of 30 years. The total funding provided by Klimatklivet, $F_{klimatklivet}$ can then be calculated by dividing the total CO_2e emission decrease of the plant with Klimatklivet's expected CO_2e emission decrease return per invested SEK, which is 2,81 kg CO_2e/SEK (Naturvårdsverket, 2020). The funding is assumed to be paid out in three equally large payments. The first payment is supplied during the first year of construction of the plant. The second payment is supplied during the second year of construction and the third payment is supplied during the first year of operation of the plant.

3.7 Cash flow analysis

Cash flows are the monetary payments in to or out of a project, such as an investment in the combined pyrolysis and CHP plant. A cash flow analysis is the process of identifying all cash flows associated with such a project and making estimates of their values (Bahadori, 2014). A cash flow analysis for an investment in the plant has therefore been conducted to estimate the value of an investment in the combined pyrolysis and CHP plant. The cash flow analysis ranges from the point in time when it is decided to start the construction of the plant and land is purchased, to one year after the end of the economic lifetime of the plant, when the plant is decommissioned, loans are paid back and land and working capital are retained. The construction of the plant is assumed to take two years and year 0 is the starting point of the cash flow analysis. At the start of the first year, i.e. the point in time to which all future cash flows are discounted, land is purchased. During year one, the cash flow consists of 25% of the FCI, which is required to begin the construction of the plant, as well as a third of the funding from Klimatklivet is paid out. During year two, the remaining 75% of the FCI is expended to complete the construction of the plant as well as another third of the funding from Klimatklivet is paid out. Just before the plant begins to operate, at the point in time between year two and year three, working capital is supplied.

To calculate the annual cash flow between year 3 and year 22, the Earnings Before Interest, Taxes, Depreciation and Amortisation (EBITDA) is first calculated. EBITDA is calculated by subtracting the OpEx from the sum of revenues for electricity, electricity certificates, heat and biochar sales. During year three, the start-up expenses must also be subtracted from the revenues to obtain EBITDA. The Earnings Before Interest and Taxes (EBIT) is then calculated by subtracting depreciation from EBITDA. The taxable income, or Earnings Before Taxes (EBT), is calculated by subtracting the interest expense from EBIT. The income tax cost is calculated as 20,6% of EBT and subtracted from EBT to obtain net profit. From the net profit, the cash flow can be calculated. To account for the heat production not being considered a revenue but rather a cost saving, the revenue from the heat production is subtracted from the net profit and instead the savings from the heat production is added. Thereafter, depreciation is added to obtain the cash flow for each year between year 3 and year 22. For year three, the last third of the funding from Klimatklivet is also added to obtain the actual cash flow. Lastly, during year 23, when the economic lifetime of the plant has been reached and the plant is decommissioned, land and working capital are retained and the loan is paid back.

The NPV of an investment in the plant is calculated by summing the discounted cash flow of each year between year 0 and year 23 as shown in equation 9. The cash flow is discounted to the time just before the construction of the plant commences, i.e. at year 0, when land is purchased. The discount rate used is set equal to the weighted average cost of capital for an investment in the plant, which is assumed to be 6%. This is similar to the weighted average cost of capital for electricity companies in Europe and large Swedish energy companies such as Vattenfall and Stockholm Exergi, as reviewed in chapter 2.6.4.

$$NPV = \sum_{t=0}^{23} \frac{CF_t}{(1+i)^t} \tag{9}$$

where:
$CF_t = Sum\ of\ all\ positive\ and\ negative\ cash\ flows\ during\ year\ t$
$i = discount\ rate$

3.8 Sensitivity analysis

To answer the MRQ of this thesis *"What are the main parameters influencing the economic feasibility of building and operating a combined pyrolysis and CHP plant?"*, two sensitivity analyses have been made to evaluate which parameters have greatest impact on the CapEx and, thus, the economic feasibility of the plant. Sensitivity analyses can, amongst other things, be used to determine the main parameters contributing to output values and the respective importance of these parameters (Park and Lek, 2016). This can be done by changing a parameter with a certain percentage while keeping all other parameters constant, performing the same calculations as previously, and observing the change of the output value (Balaman, 2019). The process is then repeated for other parameters affecting the output value.

The first sensitivity analysis was conducted by changing different parameters with +10% and -10% and thereafter evaluating how these changes influence the maximum value of the CapEx, still with the premise that an investment in the plant should have an NPV of zero. The parameters altered were: Price of sold electricity certificates, Funding from Klimatklivet, Interest rate, Price of sold electricity, Discount rate, Specific cost saving for heat, Ratio of debt financing, CHP-O&M, Number of operators, Cost for raw material and Price of sold biochar. The results from this sensitivity analysis can be used to detect which of these ten variables will have the largest impact on the maximum allowed CapEx of the plant, if an investment in the plant is to have an NPV of zero, and possibly the largest impact on the economic feasibility of the plant.

The second sensitivity analysis was conducted to evaluate the effect on the maximum allowed CapEx when the two most influential parameters were changed simultaneously. The two most influential variables from the first sensitivity analysis were both altered with ±5% and ±10%, respectively, and the value of the CapEx was observed for each alteration. Thus, the results show how these two parameters together influence the maximum value of the CapEx and can be used to see the combined effect on the maximum allowed CapEx of the plant. This provides greater insights of the economic feasibility of the plant as it is not unlikely that both parameters are concurrently altered.

4 Results and analysis

In this chapter, the results from the economic calculations of the model of a combined pyrolysis and CHP plant are presented and analysed. Firstly, the costs and benefits of constructing and operating the plant are reviewed. Secondly, the cash flow throughout the investment time horizon is investigated, and, lastly, the results from the sensitivity analysis are analysed.

4.1 Costs and benefits

With an NPV of zero, the CapEx of the plant is calculated to be approximately 500 million SEK. This is thus the value of the CapEx that makes an investment in the plant have an NPV of zero. If the CapEx would be less than 500 million SEK, the NPV will be positive, and if the CapEx would be higher than 500 million SEK, the NPV will be negative. The FCI makes up the major part of the CapEx, with working capital the second largest component followed by start-up expenses and land the smallest expense, as shown in Figure 8.

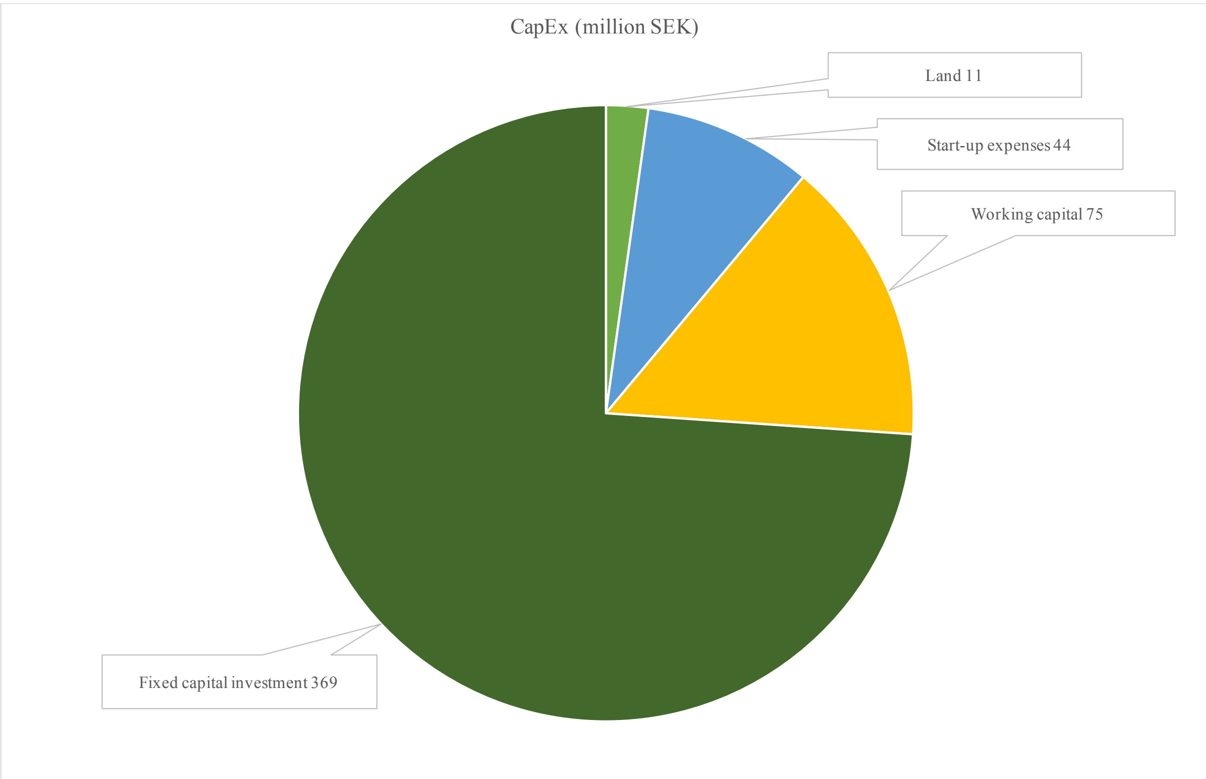

Figure 8. CapEx for an investment in the combined pyrolysis and CHP plant.

This means that if the CapEx of the plant amounted to 500 million SEK, the return on the investment would be equal to the cost of capital. The actors investing in the plant, i.e. loan providers and company shareholders, would receive their desired return on the money they invest. If possible, an investor would want to receive a higher return than the cost of capital, but if the CapEx amounted to 500 million SEK, the return on the investment would at least be equal to the minimum required return for an investment in the plant to be made. It can thus be noted that if the CapEx of the plant surpass 500 million SEK, it would not be economically feasible to construct the plant. Therefore, to further evaluate the economic feasibility of the plant, it must be discussed whether it is possible or not to construct the plant with a maximum of 500 million SEK in CapEx, which is done in chapter 5.1.

Continuing with the OpEx of the plant, it can be seen in Figure 9 that the major component in the OpEx is the cost for raw material. The cost for raw material is about three times as large as the second largest component, O&M cost for the CHP part of the plant. The third largest expense is for maintenance. However, if the maintenance expense is split up into maintenance labour and maintenance material, the third and fourth largest expenses are operating labour and payroll burden, respectively, as illustrated in Figure 9.

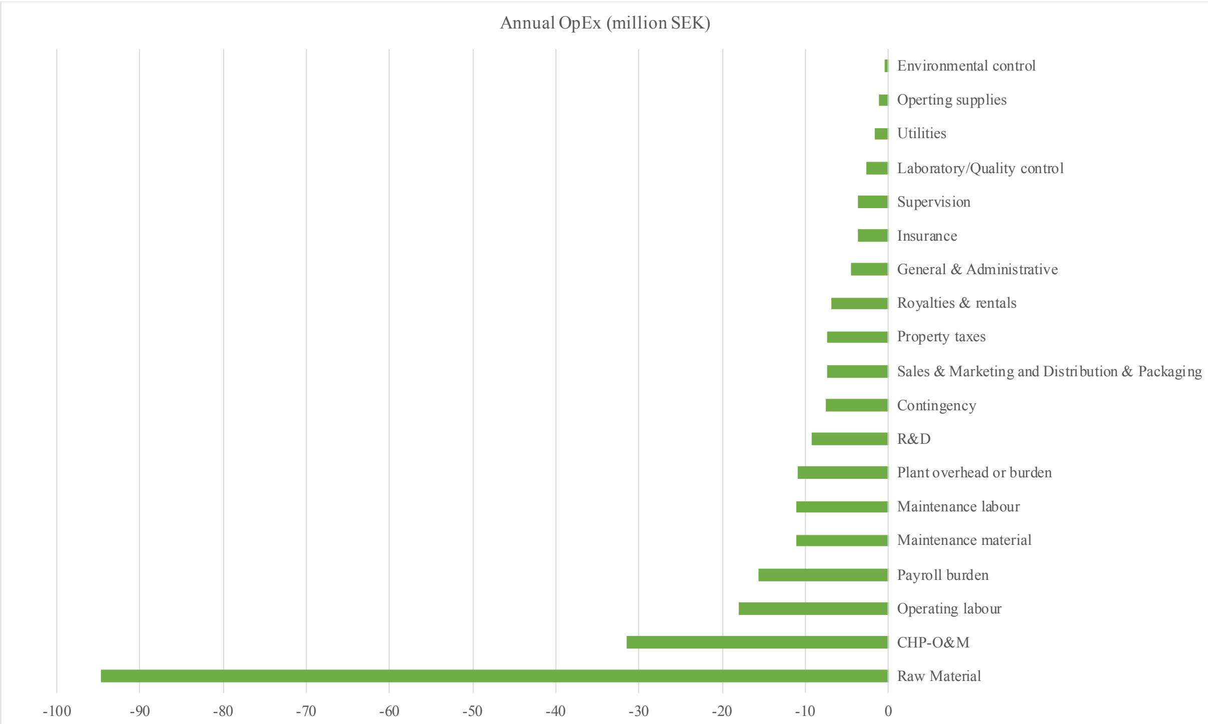

Figure 9. Annual OpEx for the combined pyrolysis and CHP plant.

As the cost for grot is by far the largest operating cost, an increase or decrease in the price for grot will have a major impact on the operating costs for the plant and, consequently, also the economic feasibility. This is further discussed in chapter 5.2.2. It can also be noted that the costs specifically related to the pyrolysis part of the plant (i.e. the sum of all costs in Figure 9 except Raw Material and CHP-O&M) are significantly larger than the costs specifically related to the CHP part of the plant (i.e. the cost for CHP-O&M). Thus, it can be said that operating the pyrolysis part of the plant is more expensive than operating the CHP part of the plant. However, this is not unexpected as more operations are required for the production, handling, and sales of a solid product, such as biochar, than what is required for electricity and heat.

In Figure 10, the annual non-operational expenses of depreciation, interest, and taxes for the plant are shown. The tax cost during year three is significantly lower than for the years 4-22 because the start-up expenses incur during year three, which lowers the EBT and, in turn, also the tax cost. Both the depreciation and interest are related to the CapEx of the plant, with higher CapEx resulting in greater expenses for depreciation and interest. The interest expense is also correlated to the debt-equity financing ratio of an investment in the plant, where a greater degree of debt financing results in higher interest expenses, which is further discussed in chapter 5.2.4. Important to note is that depreciation is not an actual monetary payment but an accounting concept where the cost of an asset is allocated equally throughout the years of the asset's lifetime.

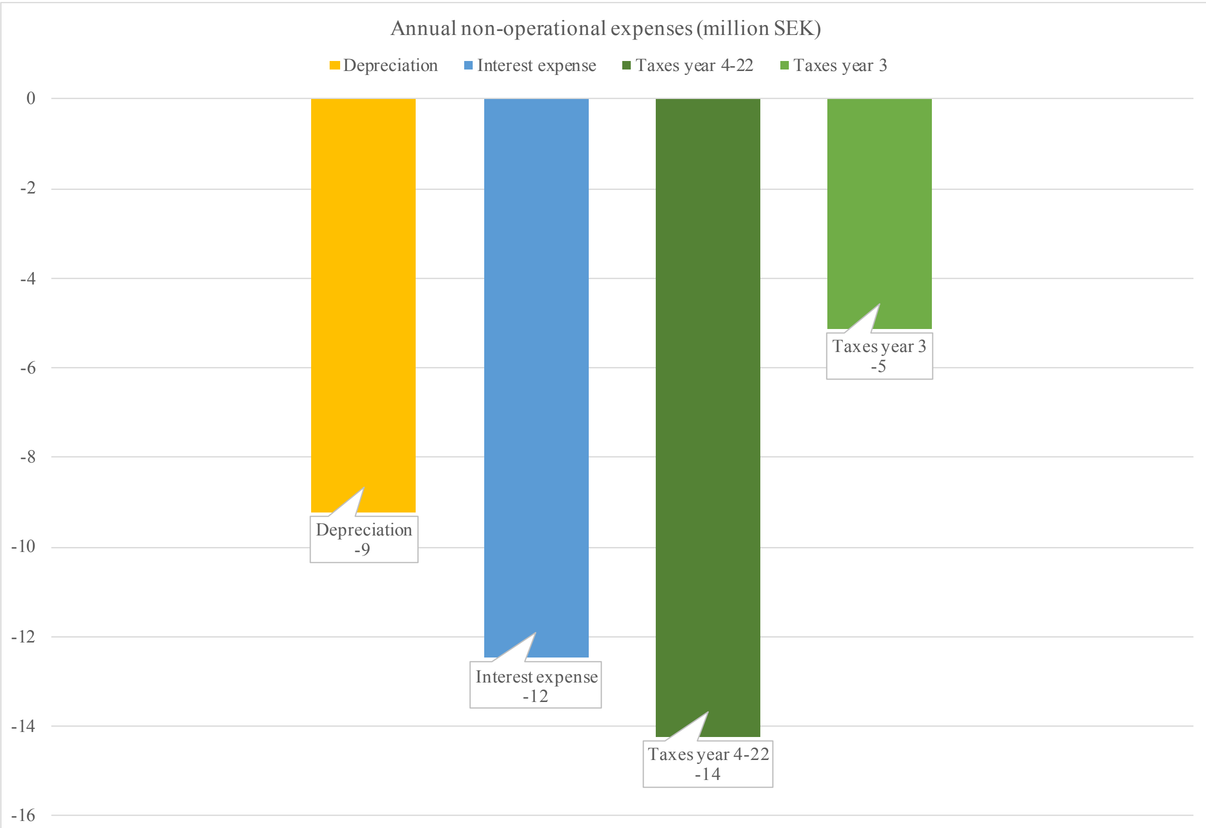

Figure 10. Annual non-operational expenses of depreciation, interest and taxes.

The benefits from the plant include sales of electricity, sales of electricity certificates, sales of biochar, cost savings from the heat production, and funding from Klimatklivet. The total funding from Klimatklivet amounts to approximately 91 million SEK, and the annual benefits stemming from the electricity, electricity certificates, heat and biochar during the economic lifetime of the plant are shown in Figure 11. The funding from Klimatklivet differs from the benefits in Figure 11 as it is paid out in three equally large payments during the first three years of the investment time horizon, while the other benefits occur annually throughout the economic lifetime of the plant.

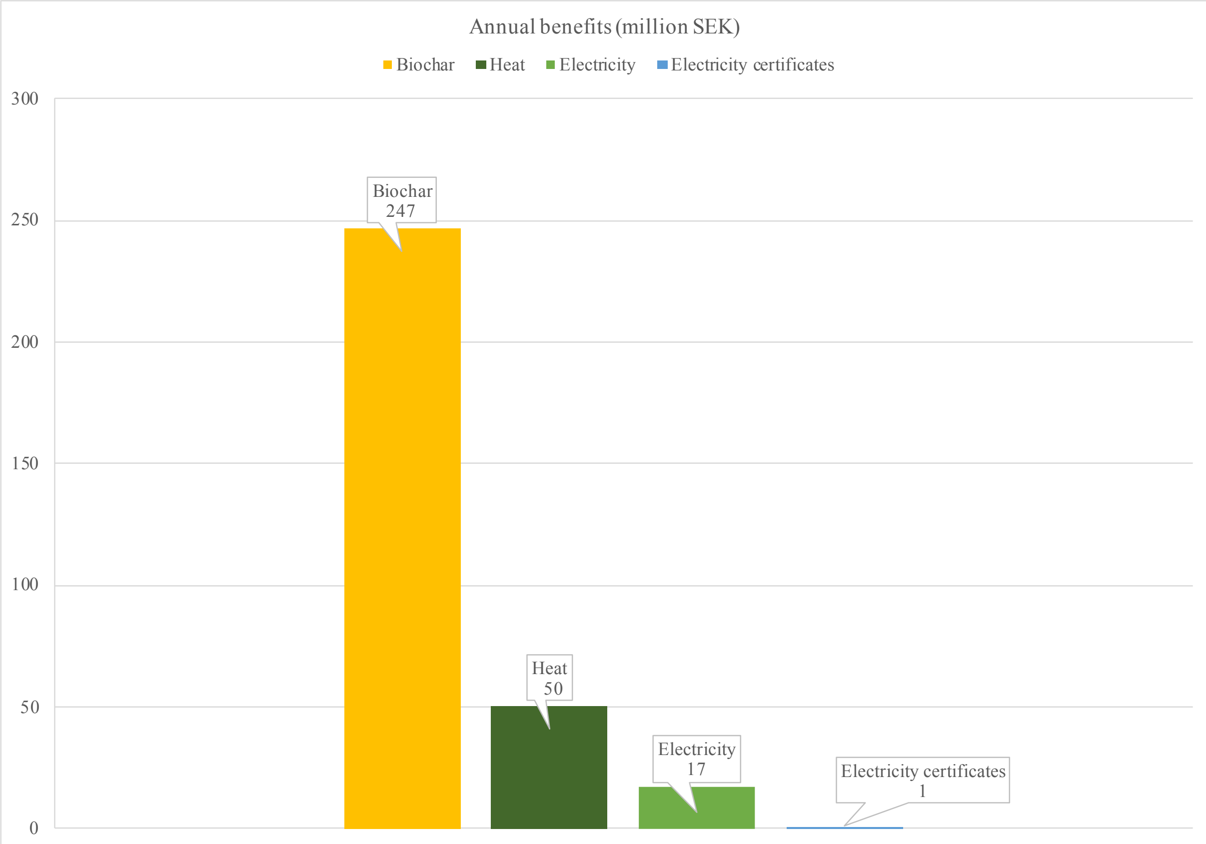

Figure 11. Annual benefits incurred throughout the economic lifetime of the plant.

4.2 Cash flows

When considering the cash flow from the benefits, it is possible to distinguish the difference between the funding from Klimatklivet and the benefits shown in Figure 11. This difference is illustrated in Figure 12, where the positive cash flows from year 0, the starting point of the investment, to year 23, the end of the investment time horizon, is shown. The funding from Klimatklivet is paid out in three equally large payments during the first three years of the investment time horizon (year 1-3), while the benefits in Figure 11 occur annually throughout the economic lifetime of the plant (year 3-22). In Figure 12, it is also apparent that the only positive cash flow during year 23, when the plant is assumed to be decommissioned, consists of retained working capital and retained land cost.

In contrast to the positive cash flows, the negative cash flows are shown in Figure 13. Before construction of the plant commences, i.e. at year 0, land is purchased. During the first year, 25% of the fixed capital investment is expended, and during year two, the remaining 75% of the FCI is expended as well as working capital is supplied. Between year three and year 22, the negative cash flow consists of OpEx, depreciation, interest and tax costs, as well as start-up expenses during year three. During year 23, the negative cash flow solely consists of the loan payback.

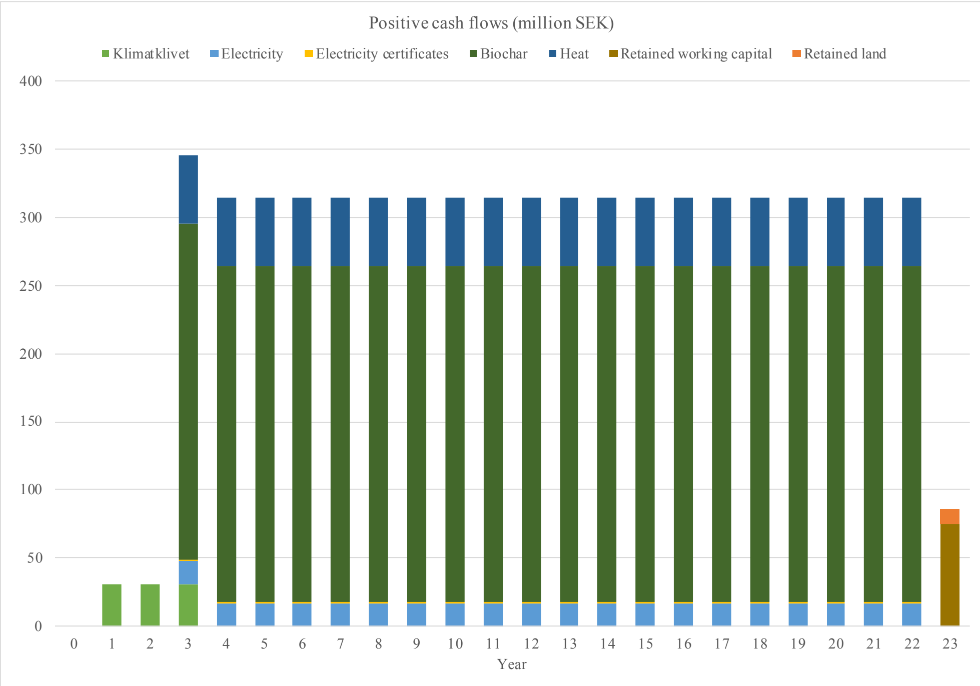

Figure 12. Positive cash flows throughout the investment time horizon.

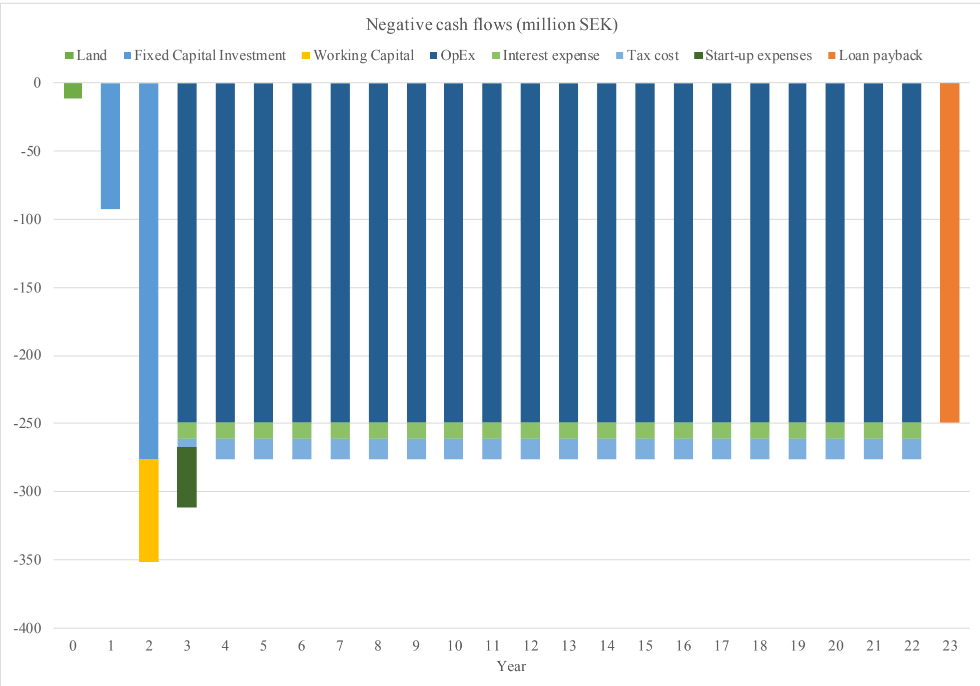

Figure 13. Negative cash flows throughout the investment time horizon.

The difference between the positive and negative cash flow, the net cash flow, is illustrated in Figure 14. As can be seen in Figure 14, the net cash flow is positive except for the first three years and the last year of the investment time horizon, year 23.

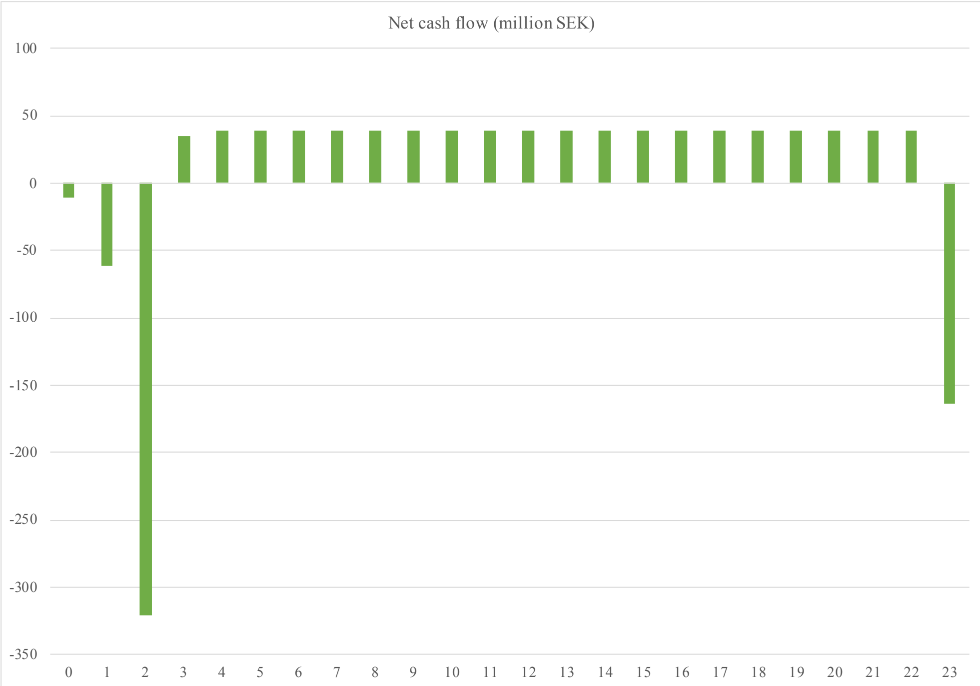

Figure 14. Net cash flow throughout the investment time horizon.

The discounted net cash flow is illustrated in Figure 15. Comparing Figure 14 and Figure 15 illustrates the time value of money as the absolute values of cash flows towards the end of the investment time horizon are smaller than the absolute values of cash flows closer to year 0. This means that cash flows closer to year 0 have a greater effect on the NPV of an investment in the plant.

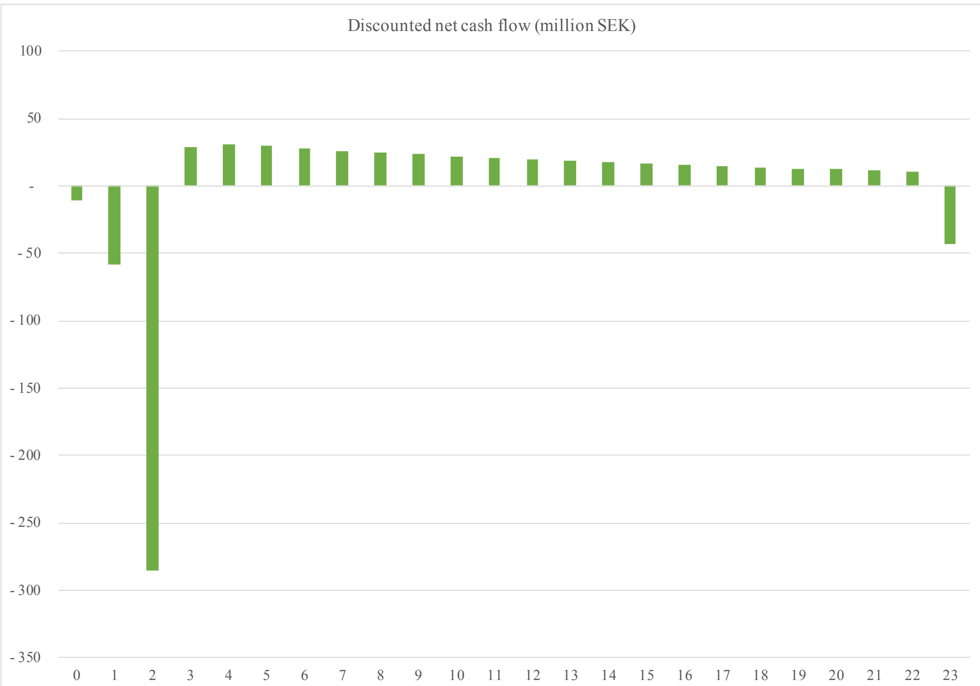

Figure 15. Discounted net cash flows throughout the investment time horizon.

In Figure 16, the accumulated discounted net cash flow is shown. In the figure, it can be seen that the accumulated discounted net cash flow for year 23, which is the NPV of an investment in the plant, is equal to zero. As the NPV of an investment in the plant is zero, the Internal Rate of Return (IRR) of the investment is equal to the discount rate, which is 6%. The discount rate is, similar to interest expense, correlated with the debt-equity financing ratio, which is discussed in chapter 5.2.4.

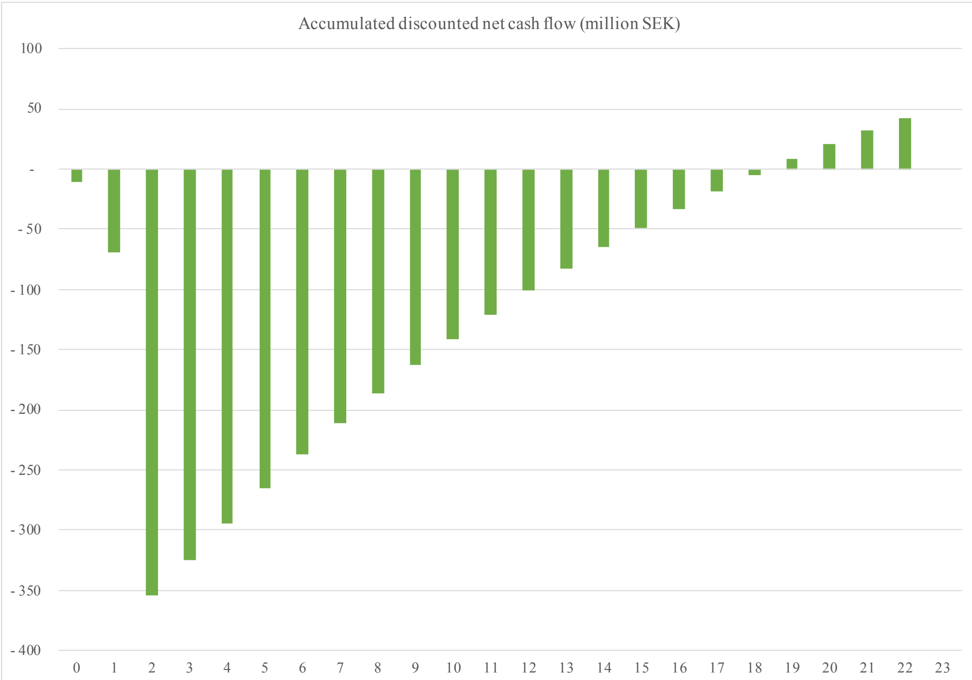

Figure 16. Accumulated discounted cash flow throughout the investment time horizon.

4.3 Sensitivity analysis

In Figure 17, the result from the first sensitivity analysis, where different parameters' influence on the maximum allowed CapEx was analysed, is illustrated in a tornado plot. From the figure, it can be seen that the price of biochar is the most influential parameter when determining the maximum allowed CapEx for the plant, if an investment in the plant is to have an NPV of zero. If the price of biochar increases with 10%, the CapEx increases with almost 100 million SEK, and, conversely, if the price of biochar decreases with 10%, the CapEx decreases with almost 100 million SEK. The price of biochar has more than twice as large of an effect on the CapEx compared to the cost of raw material, which is the second most influential factor. The cost for raw material, in turn, has around twice as large impact as the third most influential factor, the number of workers. This means that the maximum allowed CapEx of the plant, if an investment in the plant is to have an NPV of zero, is heavily dependent on the price of sold biochar. If the price for biochar would differ by 10%, the maximum allowed CapEx would differ with about 20%.

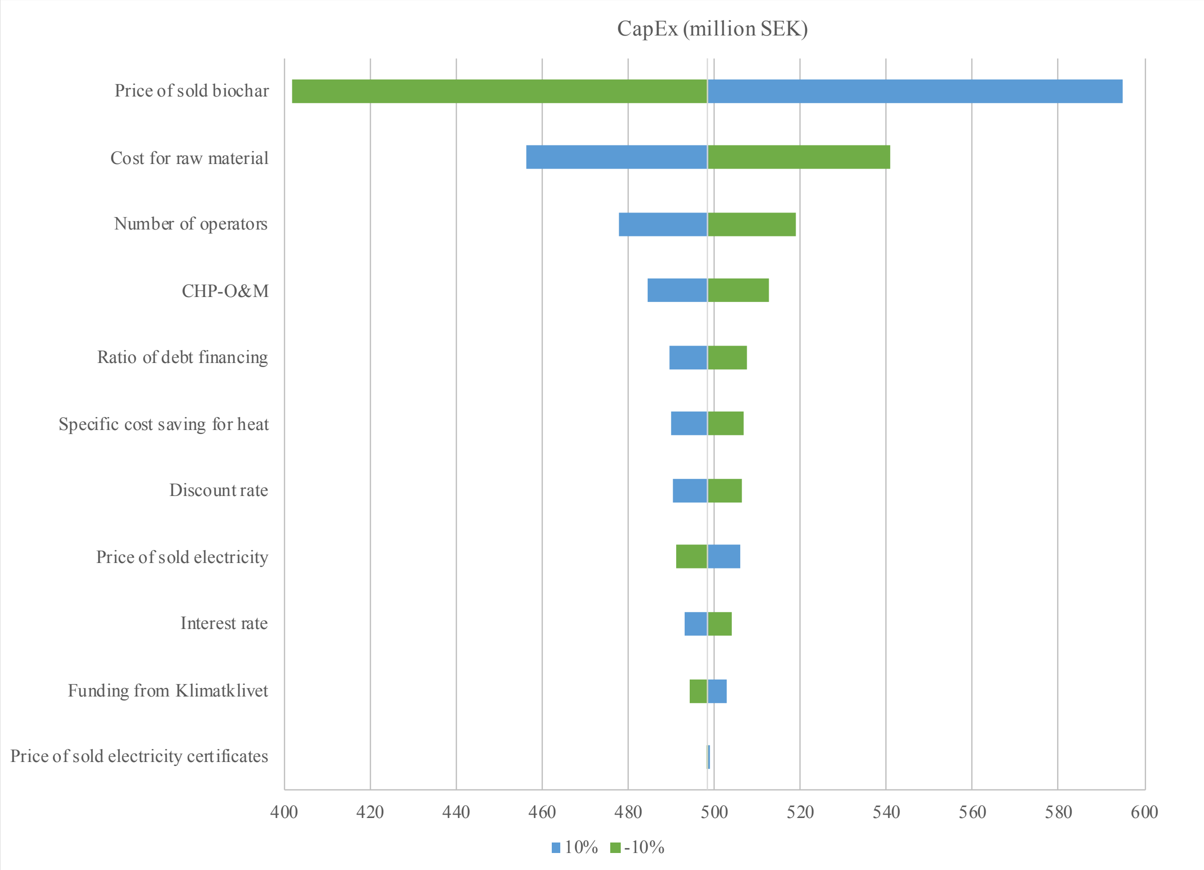

Figure 17. Different parameters' influence on the maximum allowed CapEx.

In Figure 18, the result from the second sensitivity analysis is shown. The figure displays how percentage changes of ±10% of the two most influential factors, raw material price and biochar price, affect the maximum allowed CapEx. As can be seen in the figure, the maximum value for CapEx varies between about 360 million SEK and just over 610 million SEK, depending on the price of biochar and raw material. The maximum allowed CapEx can thus differ with almost a factor two when the cost for raw material increase and the price of biochar decrease with 10%, compared to when the cost for raw material decrease and the price of biochar increase with 10%. This implies that the cost for raw material, together with the price of biochar, have a great effect on the economic feasibility of the combined pyrolysis and CHP plant.

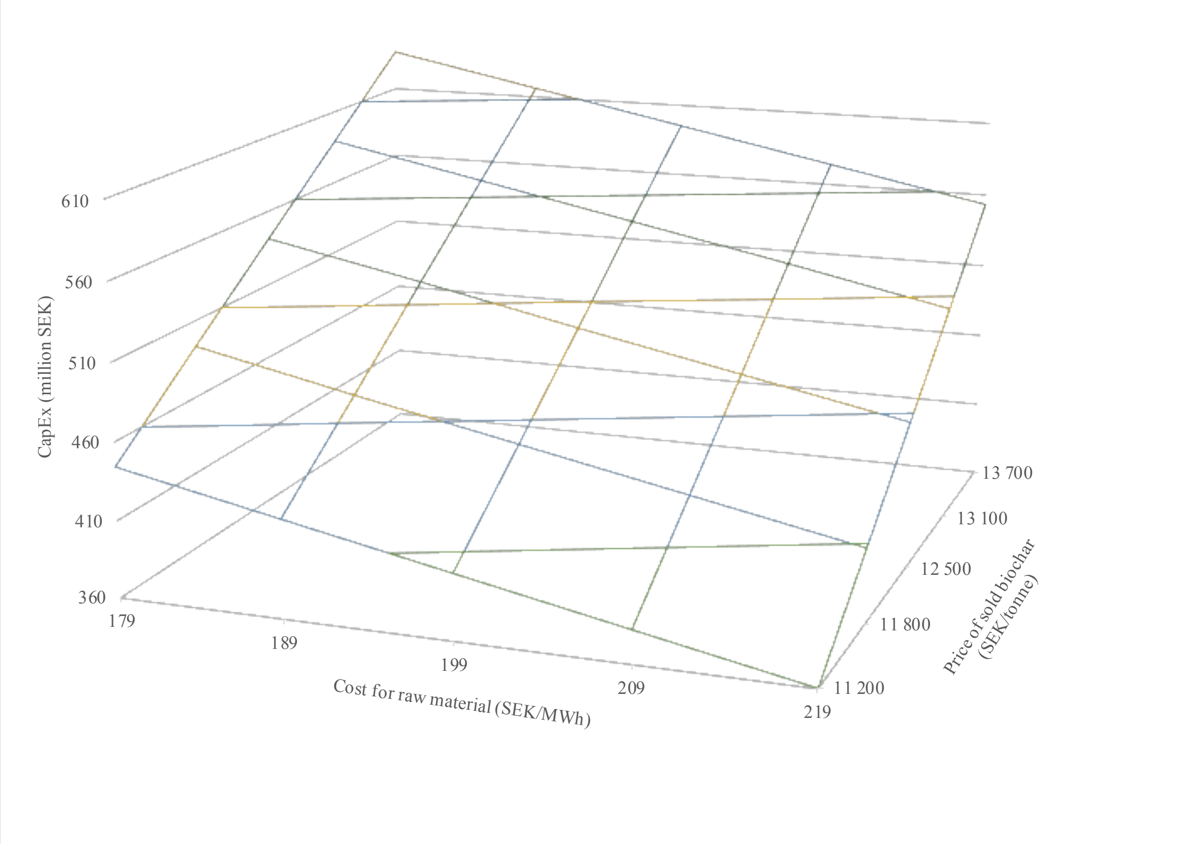

Figure 18. Effect on maximum allowed CapEx by simultaneous changes in raw material cost and biochar price.

5 Discussion

In this chapter, the economic feasibility, as well as factors influencing the economic feasibility of the combined pyrolysis and CHP plant, are discussed. Furthermore, the dynamics of technological change in the CHP sector in relation to the development of a combined pyrolysis and CHP plant are discussed. The discussion is based on the results and the analysis of the results in chapter 4 as well as on pertinent literature and the MLP-model, as presented in chapter 2.7.

5.1 Economic feasibility

To evaluate the economic feasibility of the combined pyrolysis and CHP plant, the maximum allowed CapEx of the plant, if an investment in the plant is to have an NPV of zero, can be compared to the CapEx of a CHP plant and a pyrolysis plant of similar capacity. The maximum allowed CapEx of the combined pyrolysis and CHP plant is, as presented in chapter 4, 500 million SEK. The CapEx for a biomass CHP plant of similar electricity and heat output is approximately 285 million SEK, based on a specific investment cost of 53 900 SEK/kW_e (Nohlgren et al., 2014). Assuming that the CapEx for the CHP part of the plant is equal to the CapEx for a biomass CHP plant with similar electricity and heat output, the maximum allowed CapEx for the pyrolysis part of the plant is about 213 million SEK.

The plant has an annual feedstock capacity of 80 000 oven dry tonne (odt) biomass, which means that the maximum allowed specific CapEx for the pyrolysis part of the plant is 2665 SEK/odt feedstock. This figure can be compared with the specific CapEx for a pyrolysis plant of similar feedstock capacity to evaluate whether or not it is feasible to construct the pyrolysis part of the plant for less than 2665 SEK/odt feedstock. Masek et al. (2010) write that the CapEx for a slow pyrolysis plant in Hinode-cho, Tokyo, amounted to approximately 527 million $SEK_{\$}$. They write that the annual feedstock capacity of the plant is 255 500 odt, which is equivalent to a specific CapEx of 2064 SEK/odt feedstock. Assuming that the CapEx for the pyrolysis part of the plant does not exceed the specific CapEx presented by Masek et al. (2010), and that the specific CapEx of the CHP part of the plant is 53 900 SEK/kW_e, the CapEx for the combined pyrolysis and CHP plant would be about 450 million SEK. This means that an investment in the combined pyrolysis and CHP plant would have a positive NPV.

The capital costs for pyrolysis plants are, however, affected by economies of scale, meaning that a larger feedstock capacity lowers the specific CapEx. McCarl et al. (2009) present a pyrolysis plant with an annual feedstock capacity of 70 080 odt, which is closer to the 80 000 odt feedstock capacity of the combined pyrolysis and CHP plant in this thesis. The CapEx for the pyrolysis plant presented by McCarl et al. (2009) amounted to approximately 135 million $SEK_{\$}$, equivalent to a specific CapEx of 1925 SEK/odt feedstock. This is somewhat lower than the specific CapEx presented by Masek et al. (2010) and further underlines that it could be possible to obtain a positive NPV from an investment in the combined pyrolysis and CHP plant.

Shackley et al. (2011) present the CapEx for a large and a medium-scale pyrolysis plant. The specific CapEx for the large scale pyrolysis plant, with an annual feedstock capacity of 184 000 odt, is 2120 $SEK_{\$}$/odt feedstock. The specific CapEx for the medium scale pyrolysis plant, with an annual feedstock capacity of 16 000 odt, is 4750 $SEK_{\$}$/odt feedstock. Applying a specific CapEx for the pyrolysis part of the plant comparable to the large-scale plant presented by Shackley et al. (2011), the NPV of an investment in the plant would be positive. However, applying a specific CapEx comparable to the medium scale pyrolysis plant, the NPV would be negative.

Although the comparisons above give indications that it could be economically feasible to construct and operate a combined pyrolysis and CHP plant, they are not ideal. Firstly, there might be a difference between the pyrolysis configurations in the pyrolysis part of the plant, and the pyrolysis plants presented by Masek et al. (2010), McCarl et al. (2009) and Shackley et al. (2011). The aforementioned authors do not provide information regarding the type of furnace used in the respective pyrolysis plants. It is, however, plausible to believe that the pyrolysis plants presented by the authors are not centred around an RHF, as no literature regarding the use of an RHF for pyrolysis of biomass has been found. The specific CapEx for the pyrolysis part of the combined pyrolysis and CHP plant might, therefore, differ compared to the specific CapEx presented by Masek et al. (2010), McCarl et al. (2009) and Shackley et al. (2011). Secondly, the CapEx of the CHP part of the plant may also differ from the above-mentioned figure of 285 million SEK, as there is a distinct difference between the CHP part of the plant and a conventional biomass CHP plant. In a biomass CHP plant, a boiler, such as a circulating or bubbling fluidized bed boiler, is used to combust solid biomass and generate steam. Such a boiler is not present in the plant investigated in this thesis. Instead, an HRSG is used to generate steam from hot flue gases, resulting from combustion of pyrolysis gas. Thus, the difference in configuration between a biomass CHP plant and the CHP part of the combined pyrolysis and CHP plant is likely to result in a difference in CapEx as well.

Evidently, more research is needed regarding the CapEx of the combined pyrolysis and CHP plant. Reliable data regarding the costs for major process equipment in the combined pyrolysis and CHP plant could provide a more accurate indication of the economic feasibility of the plant. Research is especially needed regarding the pyrolysis part of the plant as the pyrolysis technology is less proven and mature than the CHP technology and the costs, therefore, come with greater uncertainties. However, the figures presented by Masek et al. (2010), McCarl et al. (2009) and Shackley et al. (2011) provide support that it may be possible to construct the combined pyrolysis and CHP plant without the CapEx exceeding 500 million SEK, thus obtaining a positive NPV for an investment in the plant.

5.2 Factors influencing economic feasibility

There are many factors influencing the maximum allowed CapEx of the plant. In this chapter, the most influential factors for determining the maximum allowed CapEx and, thus, affecting the economic feasibility of the plant are discussed.

5.2.1 Biochar market

The first sensitivity analysis displays that the maximum allowed CapEx is most vulnerable to variations in market prices for biochar. This is analogous to what Campbell et al. (2018) concluded about biochar market prices having the largest effect on the profitability of stand-alone biochar production plants. Wrobel-Tobiszewska et al. (2015) also determined that the profitability of biochar production is highly dependent on the biochar price. The price of biochar used in this thesis is obtained from the average willingness to pay for biochar among soil manufacturers in Sweden, which is 2800 SEK/m^3, or about 12 450 SEK/tonne if converted using a biochar density of 225 kg/m^3. This price roughly corresponds to the price of biochar at the Swedish seed company Skånefrö. Skånefrö sells biochar, with a density of 291 kg/m^3 (Skånefrö, 2020a), in bags of 2400 litres for 9 452 SEK excluding VAT (Skånefrö, 2020b), resulting in a biochar price of about 13 500 SEK/tonne. The percentage difference between a price of 12 450 SEK/tonne and 13 500 SEK/tonne is almost 10%, which, as seen in the sensitivity analysis, had a great effect on the maximum allowed CapEx and thus the economic feasibility of the plant. Considering that biochar prices in literature range from as low as 675 SEK/tonne to as high as 84 075 SEK/tonne, it becomes apparent that the price of biochar is a decisive factor for the economic feasibility of the plant. Research regarding the price development of biochar is, therefore, of essence to be conducted for future evaluations of the economic feasibility of the combined pyrolysis and CHP plant.

It is furthermore essential to investigate whether or not it is possible to sell all the biochar produced in the plant. In this thesis, it is assumed that biochar can be sold in the quantity produced at the plant. However, there is no clear indication of the market size of biochar, especially not in Sweden. Thus, it is not certain that all biochar can be sold at a price of about 12 450 SEK/tonne. According to findings from Salo (2018), the global market for biochar is around 1 000 000 tonnes. He further writes that the Finnish market for biochar is approximately 1000 tonnes and that, of this amount, around 20% is used as soil amendment. The annual biochar produced in the plant amounts to approximately 20 000 tonnes (based on a biochar output of 2,5 tonne/hour and an annual operating time of 8000 hours). If the demand for biochar in Sweden is similar to the demand for biochar in Finland, there is a strong need for exporting biochar. Furthermore, assuming that the global market share for biochar as a soil amendment product is the same as in Finland, the plant's global market share of biochar as a soil amendment product would correspond to 10%. Although the biochar market can be seen as small, compared to the biochar production capacity of the plant, the growth rate of the biochar market is quite significant, both globally and in Sweden. Salo (2018) estimates that the global biochar market has an annual growth rate of 20-30%, and, according to a soil manufacturer in Sweden, the annual growth rate of biochar in Sweden is expected to be 10-20% (Avfall Sverige, 2018). Thus, there is a need to perform more research about the future market size of biochar to further evaluate if all biochar produced in the plant can be sold.

5.2.2 Raw material cost

From the results, it is possible to see that the cost for raw material, i.e. grot, is the largest expense of the OpEx. In the sensitivity analysis, the cost for raw material was also found to be the factor with the second largest influence on the CapEx of the plant. The cost for raw material is estimated based on the average price that heating plants in Sweden pay for grot, including transportation to the plant. In contrast to the biochar market, an established market for grot exists in Sweden. The market for grot in Sweden has, as reviewed in chapter 2.2, large potential for further growth, implying that a shortage of grot is unlikely. The price of grot has, between the years 1993-2019, had a compound annual growth rate of about 1,9%, fluctuating between 109 SEK/MWh and 199 SEK/MWh (The Swedish Energy Agency, 2020). The cost for raw material, therefore, seems to be relatively predictable, and the potential span for fluctuations is deemed to be smaller than the potential span of biochar prices, as discussed in chapter 5.2.1. Thus, although the cost for raw material has a strong influence on the economic feasibility of the plant, it is not as crucial as crucial as the price of biochar.

5.2.3 Operating labour

The parameter with the third largest influence on the maximum allowed CapEx of the plant is the number of operators needed for the pyrolysis part of the plant. If a larger number of operators are needed, the cost for operating labour would increase, which means that the maximum allowed CapEx of the plant will decrease. Vice versa, the maximum allowed CapEx of the plant would increase if fewer operators are needed. The reason why the number of operators in the pyrolysis part of the plant has such a high influence on the CapEx is because many other costs are derived from the cost for operating labour. These include costs for operating supplies, supervision & clerical labour, payroll burden, laboratory & quality control, plant overhead or burden, and general & administrative. Thus, an increase in operating labour means that the aforementioned costs also will increase. It therefore becomes important that the cost for operating labour is precisely estimated. A factor that has not been included in the estimation is synergies between the pyrolysis process and CHP process of the plant, which potentially could decrease the operating labour cost. As the processes are integrated in the same plant, it is possible that fewer operators can conduct all necessary operations, compared to the number of operators needed for the processes in two separate plants. To more accurately estimate the operating labour required for the plant, the method developed by Wessel can be used. Peters and Timmerhaus (1991) argue that this method is more accurate than the method used in this thesis. However, Wessel's method requires reviewing the flow sheet diagram of the plant, which was not available for this thesis.

5.2.4 Financing & discount rate

The CapEx of the plant is assumed to be equally financed by equity and debt, which means that 50% of the CapEx is borrowed by issuing bonds and the other 50% is supplied by issuing stocks. If the plant was fully financed by debt, the yearly interest payments would double from 12,5 to 25 million SEK. On the other hand, if the plant was fully financed by equity, the WACC and discount rate used to calculate the NPV would increase as the cost of equity is higher than the cost of debt. Consequently, an optimal debt-equity financing ratio lies somewhere in between the two extremes. This optimal ratio is dependent on factors such as the economic conditions of the plant owner and the willingness of banks to issue loans to an investment in a novel technology. As the RHF pyrolysis technology used in the plant has not been proven in practice and the biochar market is far from established, a higher cost of debt as well as a higher cost of equity could be required as investors seek higher returns for riskier investments. However, the positive climate effect of biochar sequestration might be a factor that attracts interest among sustainable investors and the government. In a British study of a pyrolysis plant by Shackley et al. (2011), it was assumed that favourable governmental lending would be provided for the capital investment, resulting in a discount rate of 8%. Although favourable lending was assumed by Shackley et al. (2011), a discount rate of 8% is higher than the discount rate used in this thesis (6%), which might suggest that a higher discount rate should be used for an investment in the combined pyrolysis and CHP plant.

5.2.5 Carbon sequestration potential of biochar

The benefit incurred from carbon sequestration is derived from funding granted by Klimatklivet. The funding is estimated based on how much CO_2e can be sequestered in the biochar, with the assumption that Klimatklivet will provide 1 SEK of funding for every 2,81 kg of CO_2e that is sequestered. This assumption is consistent with the average emission decrease of all actions that Klimatklivet has provided funding for previously (Naturvårdsverket, 2020). To calculate the CO_2e emission decrease from the plant, it is assumed that 13% of the carbon in the biochar can be accounted for as sequestered. The funding provided by Klimatklivet, using a percentage of 13, is then calculated to be about 91 million SEK. This percentage is, however, significantly lower than what is used in other studies (see for example Woolf et al., 2010, Hammond et al., 2011, and Roberts et al., 2010). A higher percentage would possibly lead to more funding provided by Klimatklivet. Using the same method for calculating the funding provided by Klimatklivet as in chapter 3.4, but applying a percentage of 80%, as used in Roberts et al. (2010), instead of 13%, means that the funding from Klimatklivet would amount to approximately 564 million SEK. This would have an immense impact on the economic feasibility of the plant. However, the largest funding provided by Klimatklivet is 159 million SEK (Naturvårdsverket, 2020), which implies that it may not be reasonable to assume that the funding from Klimatklivet would exceed this figure by more than three times.

In the future, it is also possible that carbon sequestration through biochar could be accounted for in carbon markets, such as the ETS. If this were to happen, the percentage of carbon that can be accounted for as sequestered would impact the potential revenue from carbon credits. Assuming that 13% of the carbon in freshly produced biochar can be accounted for as sequestered and a carbon market price of 265 SEK€/kg CO_2e, which is roughly the average price during 2019 for emitting one tonne of carbon dioxide equivalents (Intercontinental Exchange, 2020), the benefits from carbon credits would increase with about 1% (see calculation in Appendix A). An increase of 1% would increase the maximum allowed CapEx of the plant with about 10 million SEK, based on the results from the sensitivity analysis. However, if a higher fraction of the carbon in the biochar was accounted for as sequestered, such as 80% used in a study by Roberts et al. (2010), the increase in biochar benefits would be almost 6% (see calculation in Appendix A). This would have a much larger effect on the maximum allowed CapEx, increasing with about 50-60 million SEK based on the results from the sensitivity analysis. It should also be noted that if the price for carbon credits in a carbon market, such as the ETS, increase, the revenue from potential carbon credits will increase as well.

5.3 Technological change in the CHP sector

In this chapter, the dynamics and characteristics of technological change in the CHP sector are discussed in relation to the development of the combined pyrolysis and CHP plant. A sociotechnical perspective using the MLP-model, as presented in chapter 2.7, is applied throughout the discussion. The MLP is used as it can help understand how technological changes come about and thus provide additional knowledge of the development and feasibility of the plant.

According to Geels (2011), it is important to define the topic of analysis when using the MLP to clarify the boundaries of the analysis. Without a clearly defined topic of analysis, it can be difficult to use the MLP as an incremental innovation using one topic of analysis can be seen as a radical innovation using another topic of analysis (Rennings et al., 2010). In this discussion, the CHP sector is set as the topic of analysis as the combined pyrolysis and CHP plant investigated in this thesis is primarily related to the CHP sector.

5.3.1 CHP sector

The CHP technology is well established and there is little risk involved in utilising and developing the technology (Breeze, 2018). Thus, it can be said that the CHP sector lies in the regime level in the MLP. There exists a set of rules and practices that are used to create incremental innovations along predefined trajectories, and a key trajectory in the CHP sector is to decrease environmental impact (Thorin et al., 2015; Mago et al., 2009; Unterwurzacher, 1992). Decreasing the environmental impact in the CHP sector can be done through increased energy efficiency (Weber, 2003), switching from fossil fuel, such as coal, to cleaner fuel, such as biomass, (Thorin et al., 2015; Unterwurzacher, 1992), or using CCS (Rennings et al., 2010), for example through BECCS to produce carbon negative heat and power (Levihn et al., 2019).

The trajectory of decreased environmental impact can be seen as a result of greater environmental concern in the landscape level, putting pressure on the regime level to change (Unterwurzacher, 1992). Geels et al. (2017), mean that citizens are motivated by information about climate change threats and positive communication about the social, economic and, cultural benefits of innovations in low-carbon technologies. As values in society and the landscape level change, and the public grows more aware of the threat of global warming, changes in the regime level and the CHP sector are enabled. Society can encourage governmental funding of sustainable technologies and put pressure on politicians to expand energy and environmental policy. Geels (2010), writes that sustainable transitions may require increasing pressure from public opinion to change policies. Potential policies that could be expanded by changes in the landscape and affect the CHP sector are carbon credits and governmental funding, such as Klimatklivet. As discussed in chapter 5.2.5, if biochar was included in a carbon market, the revenue from producing biochar would increase, especially if a higher fraction of the carbon in the biochar is accounted for as sequestered. The future of biochar being included in a carbon market is, however, outside the control of single actors in the CHP sector. It is ultimately up to politicians to decide the future of biochar's inclusion in a carbon market. Research and lobbying could influence future policies and beliefs in the landscape level, but regime actors have little or no influence over the sociotechnical landscape (Geels et al., 2017).

5.3.2 Development of a combined pyrolysis and CHP plant in the CHP sector

Using the MLP to analyse the development of a combined pyrolysis and CHP plant in the CHP sector, the question of whether the plant is seen as a radical innovation in a niche or an incremental innovation in the regime must be raised. Sophisticated pyrolysis technologies have been used by humankind for hundreds of years (Garcia-Nunéz et al., 2017), and the CHP technology is well established in society, providing electricity and heat to households and industries since the beginning of the twentieth century (Weber, 2003). Furthermore, the plant is in line with the trajectory of decreased environmental impact in the CHP sector. Thus, the combined pyrolysis and CHP plant could be seen as an incremental innovation in the CHP sector. However, research regarding carbon negative heat and power in the CHP sector, such as CHP coupled with CCS, is lacking (Levihn et al., 2019), and literature regarding combined pyrolysis and CHP plants is scarce. Introducing a new product, namely biochar, could also be seen as a radical change for the CHP sector, indicating that the plant is a radical innovation for the CHP sector. This conflict may suggest that the combined pyrolysis and CHP plant is a hybridisation between a niche-innovation and an incremental innovation in the regime level, similar to coal power plants with CCS being a hybridisation between a niche-innovation and the regime (Geels, 2018).

In order for a hybridisation, such as a combined pyrolysis and CHP plant, to develop in the CHP sector, hardships related to the trajectory of decreased environmental impact must be overcome. Geels (2010) writes that transitioning to more sustainable energy systems is difficult because current energy systems are "stabilized by lock-in mechanisms that relate to sunk investments, behavioural patterns, vested interests, infrastructure, favourable subsidies and regulations" (p.495). Furthermore, Rennings et al. (2010) write that "The future potential of radical innovations in the field of power plant technology is to be regarded as relatively low, especially due to technological uncertainty, market uncertainty and sunk costs" (p.331). Sunk costs can thus be regarded as a key barrier for the CHP sector to overcome to transition to more sustainable solutions.

Although economically irrelevant for current financial choices, sunk costs strongly affect the present (Ellerman, 1996). Johnson and Keith (2004), for example, point out that sunk costs are the reason why many fossil fuelled power plants are still in operation. With the current economic, technical, and regulatory environment, these fossil fuelled power plants would never have been built. However, because capital investments have already been made in these plants, they can be competitive with new plants (Johnson and Keith, 2004). Therefore, instead of building entirely new plants (called greenfield plants) with less environmental impact, it is not uncommon to investigate if existing plants (called brownfield plants) can be retrofitted to use cleaner fuel, such as biomass. Retrofitting a brownfield plant means that a smaller capital investment is needed than if a greenfield plant was constructed (Ellerman, 1996), thus partly overcoming the barrier of sunk costs. Example of studies that have explored a retrofit of a fossil fuelled CHP plant to become more environmentally friendly include, but are not limited to, Starfelt et al. (2015), Pavlas et al. (2006) and Touš et al. (2011).

Retrofitting could also be used to redesign an existing power plant into a combined pyrolysis and CHP plant and thus obtain carbon negative heat and power. Instead of constructing a greenfield combined pyrolysis and CHP plant, a brownfield plant could be retrofitted by using some of its existing components and infrastructure. The idea of retrofitting, however, opens up questions regarding how well-suited different brownfield plants are for such reconstruction (Lawal et al., 2011). The combined pyrolysis and CHP plant makes use of similar major process equipment as combined cycle power plants, namely an HRSG and a steam turbine. The major process equipment in combined cycle power plants are a gas turbine, an HRSG, and a steam turbine (Patil et al., 2018). The gas turbine produces electricity using a gas, such as natural gas, and the exhaust gases are recovered in an HRSG, which generates steam. The steam is then utilised to produce electricity in a steam turbine and could also be condensed to produce heat. It would, therefore, be of interest to perform techno-economic analyses of retrofitting combined cycle power plants into combined pyrolysis and CHP plants.

It could also be of interest to investigate the retrofitting of biomass CHP plants. Biomass CHP plants already have infrastructure in place for handling biomass, such as grot, and could, therefore, be favourable to retrofit into a combined pyrolysis and CHP plant. However, a factor that could affect the feasibility of retrofitting a biomass CHP plant is the annual operating time of the plant. On average, biomass CHP plants in Sweden have an annual operating time of 4000 hours (Bioenergi, n.d.), which is considerably lower than what is assumed for the combined pyrolysis and CHP plant in this thesis (8000 hours). On the other hand, industrial biomass CHP plants can have an annual operating time of up to 8000 hours (Bioenergi, n.d.), which may suggest that industrial biomass CHP plants are more suitable for integration with a pyrolysis process. The annual operating hours of a CHP plant can also be dependent on the size, location and specific demand profiles for heat and power.

5.3.3 Limitations to using MLP

A limitation to using the MLP for analysing the development of a combined pyrolysis and CHP plant is that the MLP "largely focuses on changes involving significant novelty. This leads to overlooking changes in deployment of already existing technologies requiring only incremental innovation" (Cherp et al., 2018, p.181). As discussed earlier, a combined pyrolysis and CHP plant is not solely seen as a novelty. It is in line with the trajectory of decreased environmental impact in the CHP sector, and is based on existing knowledge regarding pyrolysis and CHP technology. Therefore, the plant is rather seen as a hybridisation between a radical niche innovation and an incremental innovation in the regime level. Other theoretical frameworks, with a larger focus on incremental innovations, might provide additional insights into the development of the plant in the CHP sector. Another limitation to using a sociotechnical perspective, such as the MLP, is that a political perspective is somewhat lacking (Cherp et al., 2018). The development of a combined pyrolysis and CHP plant is, as discussed in chapter 5.2.5, dependent on political factors, including governmental support through Klimatklivet and the inclusion of biochar in a carbon credit market. This means that a political perspective could be applied to better understand what the political landscape regarding biochar looks like and how it affects the development of a combined pyrolysis and CHP plant.

6 Conclusions

To evaluate the economic feasibility of a combined pyrolysis and CHP plant, the maximum allowed CapEx for the plant, with the premise that the NPV of an investment in the plant should be zero, was calculated and compared to the CapEx for a biomass CHP plant and the CapEx for a pyrolysis plant. The maximum allowed CapEx was calculated to be about 500 million SEK. The CapEx for a biomass CHP plant with similar electricity and heat output have been calculated to be around 285 million SEK, and the CapEx for a pyrolysis plant with similar feedstock capacity have been estimated to be around 135 million SEK. It is, therefore, concluded that it could be economically feasible to construct and operate a combined pyrolysis and CHP plant based on the proposed model. There are, however, several parameters that severely impact the resulting CapEx from the NPV equal to zero calculation. The parameter that has the highest impact, which can be considered to provide a high level of uncertainty, is the sales price of biochar. An increase or decrease of the biochar price with 10% will greatly influence the maximum allowed CapEx and the price of biochar range far more than 10% in literature. The economic feasibility of building the plant is therefore highly affected by the price of biochar. The cost of grot is also influential in determining the economic feasibility of the plant. However, since the market for biomass and grot in Sweden is more established than the market for biochar, this factor is not deemed as crucial for the economic feasibility of the plant as the biochar price.

Furthermore, care must be taken when comparing the CapEx for a combined pyrolysis and CHP plant with the CapEx for other pyrolysis plants and the CapEx for biomass CHP plants. Firstly, pyrolysis plants, for which data of CapEx exists, are most likely not centred around the same type of furnace as the combined pyrolysis and CHP plant investigated in this thesis is centred around, namely an RHF. This means that the CapEx for the pyrolysis part of the plant presumably differ, compared to the figure of 135 million SEK, as presented above. Secondly, in stand-alone biomass CHP plants, the CHP production is centred around a boiler that combusts solid biomass to generate steam. In the combined pyrolysis and CHP plant investigated in this thesis, the CHP production is centred around an HRSG that utilises hot flue gases to generate steam. The difference in configuration for generating steam is expected to affect the CapEx as well.

A factor that also has a great influence on the economic feasibility of the plant is the fraction of carbon contained in freshly produced biochar that can be accounted for as sequestered. In this thesis, a quite conservative fraction of 13% has been applied. However, literature suggests that much higher figures, up to 80%, could be applied. This could increase the funding provided by Klimatklivet from approximately 92 million SEK up to 564 million SEK. Moreover, in the future, if biochar is included in a carbon market, such as the ETS, the fraction of carbon, which can be accounted for as sequestered, will also have a great impact on the revenue streams of the plant. With a higher fraction of carbon accounted for as sequestered, the potential revenue from carbon credits will increase. The potential revenue from carbon credits is also dependent on the price for carbon credits, with higher prices resulting in larger revenue and vice versa.

SRQ1, "*What are the costs of building and operating a combined pyrolysis and CHP plant?*", and SRQ2, "*What are the potential economic benefits from a combined pyrolysis and CHP plant?*", of this thesis were covered in chapter 4, where the costs and benefits from a combined pyrolysis and CHP plant were presented. From the answers of SRQ1 and SRQ2, the sensitivity analyses, and the discussion in chapter 5, it was possible to answer the MRQ of this thesis "*What are the main parameters influencing the economic feasibility of building and operating a combined pyrolysis and CHP plant?*". The main parameters influencing the economic feasibility of building and operating a combined pyrolysis and CHP plant are the price of biochar, the cost for raw material, and the fraction of carbon in freshly produced biochar that can be accounted for as sequestered.

SRQ3 of this thesis, "*What are the main characteristics of technological change in the CHP sector and how do they affect the development of a combined pyrolysis and CHP plant?*", was discussed in chapter 5.3. It is concluded that technological change in the CHP sector is mainly characterised by lock-in effects due to significant sunk costs in existing plants and infrastructure. This slows down and hinders the development of new power plants, including combined pyrolysis and CHP plants. The development of a combined pyrolysis and CHP plant is thus dependent on how well sunk costs can be handled. The development of a combined pyrolysis and CHP plant could be facilitated by retrofitting existing CHP plants, as sunk costs are partly overcome. From a technological perspective, combined cycle power plants are deemed to be suitable for such retrofitting as the major components of an HRSG and a steam turbine in a combined cycle power plant are also used in the combined pyrolysis and CHP plant. However, biomass CHP plants could also be suitable for retrofitting as infrastructure for handling biomass is already in place in these plants.

To further evaluate if a combined pyrolysis and CHP plant could be economically feasible, research should focus on obtaining more accurate estimations of the biochar market in Sweden, both regarding its size and the price of biochar. Furthermore, the carbon sequestration potential of biochar, produced in the combined pyrolysis and CHP plant, should be investigated to a greater extent to better estimate benefits derived from carbon sequestration. Retrofitting of combined cycle power plants and biomass CHP plants should also be investigated from a techno-economic perspective to increase knowledge of the feasibility of such retrofitting. Lastly, more research regarding the capital costs of the combined pyrolysis and CHP plant, especially regarding the cost of major process equipment and, in particular, the cost of an RHF, is needed. Such research can be used to further ascertain whether or not a combined pyrolysis and CHP plant could be economically feasible and thus be an effective method for CDR.

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Appendix A

Using equation A, the potential revenue from carbon credits for biochar sequestration can be calculated.

$$R_{carbon\ credits} = F_{carbon\ sequestered} * A_{carbon\ in\ biochar} * P_{carbon\ credits} * C_{carbon\ to\ CO_2e} \quad \text{(A)}$$

where:

$R_{carbon\ credits} = Revenue\ from\ carbon\ credits\ (SEK/tonne\ biochar)$

$F_{carbon\ sequestered} = Fraction\ of\ carbon\ in\ biochar\ accounted\ for\ as\ sequestered$

$A_{carbon\ in\ biochar} = Amount\ of\ carbon\ in\ biochar = 0{,}909\ tonne\ carbon/tonne\ biochar$

$P_{carbon\ credits} = Price\ of\ carbon\ credits = 265\ SEK/tonne\ CO_2e$

$C_{carbon\ to\ CO_2e} = Carbon\ expressed\ in\ terms\ of\ CO_2e = 3{,}67\ CO_2e/\ carbon$

Below, the potential revenue from carbon credits is calculated for two scenarios where different fractions of carbon in biochar accounted for as sequestered are applied.

1) If the fraction of biochar accounted for as sequestered, $F_{carbon\ sequestered}$, is set to 13%, the revenue from carbon credits, $R_{carbon\ credits}$, is equal to about 115 SEK/tonne biochar. This means that the revenue from biochar increase from about 12 450 SEK/tonne biochar to 12 565 SEK/tonne biochar, i.e. an increase of approximately 1%.

2) If the fraction of biochar accounted for as sequestered, $F_{carbon\ sequestered}$, is set to 80%, the revenue from carbon credits, $R_{carbon\ credits}$, is equal to about 707 SEK/tonne biochar. This means that the revenue from biochar increase from about 12 450 SEK/tonne biochar to 13 157 SEK/tonne biochar, i.e. an increase of approximately 6%.